Structuration of Knowledge on Process Design and Evaluation for Risk-Based Decision Making

(リスクに基づく意思決定のためのプロセス設計及び評価に関する知識の構造化)

by

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Abstract

Chemical substances have become inevitable for all kinds of products, services, and consumptions. The benefits due to the utilization of chemicals are the important foundation of industries and consumers. In the contrast to the positive aspects of chemical substances, some chemicals have been marked, concerned carefully, and finally, regulated, because of the previous accidents, damages, and impacts on the environment, health, and safety (EHS). The design and operation of process system should be able to address such risk originating from decision. Various methods and technologies have been developed for supervising the positive and negative aspects of chemical substances. The implementation of such knowledge on process systems engineering into practice has been necessitated.

This thesis presents the structuration of knowledge on process design and evaluation for risk-based decision making, where different assessment methodologies such as LCA and RA are appropriately applied on their perspectives and logically connected with business activities in practicable style. The risk-based decision making should be considered not only at the early design phase of process and project, but also at the process improvement phase. For activating such continuous improvements, the practicability of risk-based approaches is enhanced. The actual case study of implementing risk-based decision making was performed on the design of metal cleaning.

Knowledge structuration was defined in this thesis as five acquisition and conversion concepts of knowledge: experience and experiment, reasoning analysis, association, extended association, integration with activity, and activation by mechanism. The related knowledge on process design and evaluation was divided into five categories of knowledge: the methods of risk specification (RSM), evaluation (EvM), alternative generation (AGM), process simulation (PSM), and risk interpretation (RIM).

A method of associating LCA and RA into decision making was developed for EvM. The meanings of indicators in LCA and RA were carefully analyzed. The main difference of them is the temporal and spatial aspects of evaluated risks. Based on the objectives of assessment and decision making, the knowledge on process evaluation should be connected with design activities. For appropriate and effective utilization of different assessment methodologies, RSM for selecting risk indices and indicators was proposed on the basis of scientifically- and practically-validated logic. Additionally, the attributions of risk indices and indicators were specified as the temporal and spatial aspects, to associate the knowledge on assessment. These enable the comprehensive consideration of risk occurred by decision.

For AGM based on the evaluation results of process in use, the requirements of process models were defined, and they were developed through reasoning and associating the evidences from experiments by actual industrial machine and CFD analysis. Obtained knowledge on process behavior was stored as decision tables for alternative generation. Based on the needs from EvM and AGM, quantitative process models for PSM were developed by physical analysis. Such models enable the evaluation of alternative processes. The way of interpreting all evaluation results can be based on RIM enabling absolutely understanding of the physical meanings of risk indices and indicators and relatively comparison of the evaluation results. Both are available in risk-based decision making, and knowledge utilized in risk specification can be useful resources.

The interaction of each method was analyzed and implemented into a business model visualized by IDEF0 function modeling language. At the same time, the information system models required for the activation of risk-based decision making can be discussed and modeled by IDEF1x and UML information modeling languages. The combination of these modeling languages can visualize the achievements of knowledge structuration.

The general applicability of knowledge structuration and proposed structured knowledge on process design and evaluation was verified by discussion on the inclusion of them into the existing concept for process improvement. The effective and appropriate implementation of such scientific knowledge into practice needs several models on activity and information. For making it more effective, the templates for strategic problem identification, knowledge structuring, business activity, and software information modeling were developed.

In summary, this thesis proposes the templates of promoting knowledge structuration as well as appropriate structured knowledge on process design and evaluation. The pentagonal knowledge structure and its business activity and supporting software system models are the scenario-based framework of applying engineering and scientific knowledge into practice in risk-based decision making. It can be a strong milestone for the knowledge structuration implementing distributed knowledge, skill, technology, and heuristics into practice for improving decision making for sustainable future.

Contents

Chapter 1. Introduction

1.1. Risk Control for Supervising Chemical Benefit

Chemical substances have become inevitable for all kinds of products, services, and consumptions. All products are composed of chemicals with a significant amount of the consumptions of process chemicals. The benefits due to the utilization of chemicals are the important foundation of industries and consumers. In the contrast to the positive aspects of chemical substances, some chemicals have been marked, concerned carefully, and finally, regulated, because of the previous accidents, damages, and impacts on the environment, health, and safety (EHS). Seveso (1976) and Bhopal (1984), the major environmental pollutions in Japan, and ozone depletion problems are the famous negative events on chemical substances behind the generation of chemical benefits. Against noticeable hazards of chemicals, laws and regulations have been enacted all over the world. In Japan, starting at the Poisonous and Deleterious Substances Control Law, enacted basically in 1912 (MHLW 2008), various laws regulated specific chemicals, such as the Industrial Safety and Health Law in 1947 (MHLW 2008) and the Agricultural Chemicals Regulation Law in 1948 (MAFF 2008) for dichlorodiphenyl trichloroethane (DDT) etc. On the basis of the problems of environmental pollutions in Japan, the Air Pollution Control Law in 1968 (MOEn 2006) and the Water Pollution Control Law in 1970 (MOEn 2008a) were established to address the emission control, which were based on the Basic Law for Environmental Pollution Control in 1967, which was abolished and transferred to the Basic Environment Law in 1993 (MOEn 2008a). The Soil Contamination Countermeasures Law in 2002 (MOEn 2008) concerned the pollution of soil by emitted chemicals. International chemical regulations were also taken into account, e.g., the Law Concerning the Protection of the Ozone Layer through the Control of Specified Substances and Other Measures (MOEn 2008a) concerning the Montreal Protocol in 1988. These laws and regulations were based on the hazardous properties of chemicals, for example, the poisonous and deleterious substances are defined as the chemical substances with LD50 less than 50 mg·kg^{-1} between 50 and 300 mg·kg^{-1}, respectively.

All chemicals have more or less intrinsic hazardous properties. When it is used a lot and the environment and human expose to it significantly, the damage and impact due to the use of them should be taken into account as sufficiently high risks to be reduced, even though the chemicals have small hazards. At the same time, even for a chemical substance with relatively high hazards, when the amount of the exposure of environment and human is little, the use of it should be accepted, as the results of the adequate risk management. **Figure 1-1** schematically shows the difference of hazard and risk managements. Risk management has been considered as a measure to reach a reasonable conclusion compromising the balance between chemical risks and benefits.

Based on the international trend from hazard management to risk management, laws and regulations moved from the prohibition to the notification of the release and transfer of chemicals. **Figure 1-2** shows the increase of regulated chemicals by Japanese laws, which are the Law Concerning the Evaluation of Chemical Substances and Regulation of their Manufacture in 1973 (METI 2008, MHLW 2008, MOEn 2008a) and the Act on Confirmation, etc. of Release Amounts of Specific Chemical Substances in the Environment and Promotion of Improvements to the Management Thereof (METI 2008, MHLW 2008, MOEn 2008a). According to **Figure 1-2**, whereas the number of chemicals prohibited for their productions, imports and use was not increased recently, that of chemicals to be notified has kept increasing significantly. Such chemicals have hazardous properties, but not too large to ban the productions, imports, and use, and the most of them have been applied to generate great chemical benefits.

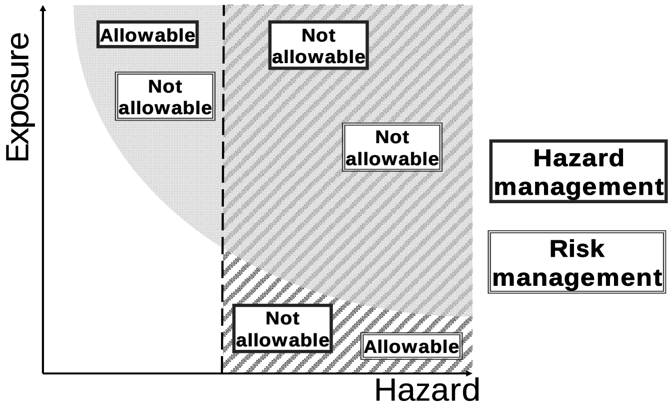


Figure 1-1 Risk-based and hazard-based managements of chemical substances

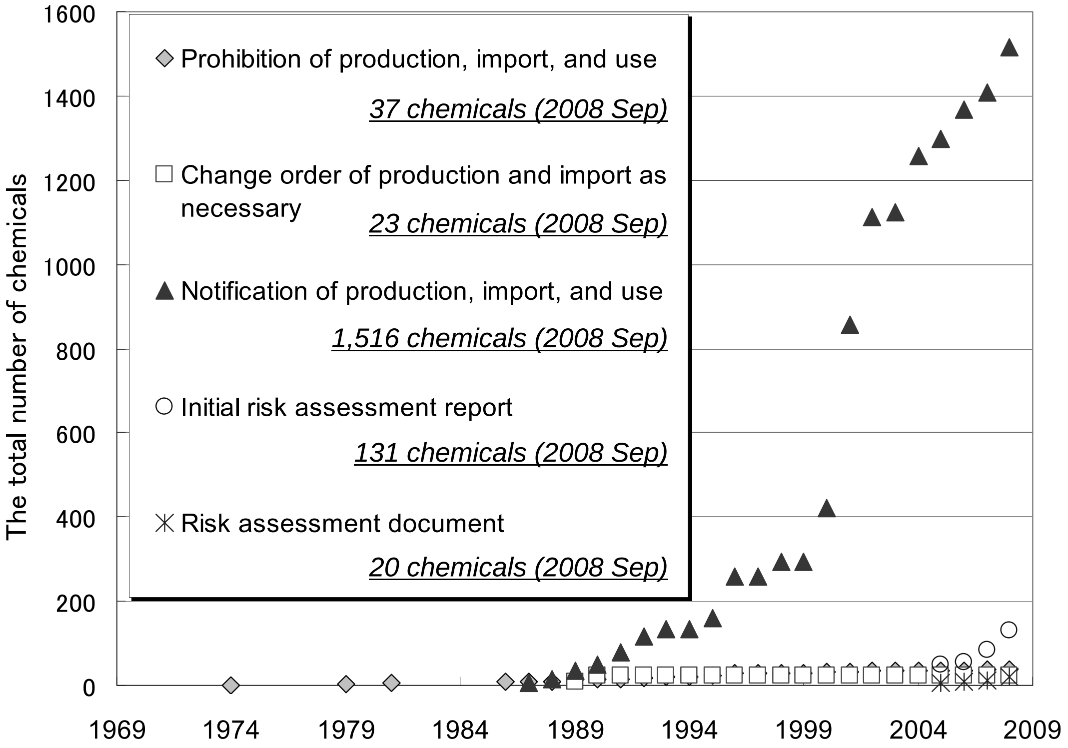


Figure 1-2 Increase of regulated chemicals by Japanese laws: The Law Concerning the Evaluation of Chemical Substances and Regulation of their Manufacture and the Act on Confirmation, etc. of Release Amounts of Specific Chemical Substances in the Environment and Promotion of Improvements to the Management Thereof.

For the appropriate risk management, the national institutes on chemical risks in several countries generally performed the initial or in-depth risk assessments of specific chemicals (US-EPA 2008a; European committee 2008; NITE 2008). These risk assessments have been able to reveal and quantify the general chemical risk due to the utilization of them as raw materials and process chemicals. Based on the results of them, the risk control is considered as an institution of laws and regulations. What enables such useful assessments might be the nation-wide chemical substances and emissions investigation, one of which is the pollutant release and transfer register (PRTR) investigation in Japan started in 2001 (MOEn 2008b).

Figure 1-3 shows manufacturing sector-based overview of the relationships among product, added value in 2006 (METI 2008) and notified emission by PRTR investigation on 2006 (MOEn 2008b). Although chemical risks may be regarded as the problems in chemical industry, the statistical results shown in **Figure 1-3** indicate that such problems must be concerned by all kinds of manufacture, obviously. Some sectors have the same or larger magnitudes of emission, comparing the emission from chemical industry. At the same time, the high product and added value do not always need the high emission of chemicals, although the emission seems to be necessary compensation for achieving the required process functions of each manufacturing industry.

Figure 1-4 shows the contributions of each employer of chemicals to the results of PRTR investigation for the total emission in Japan 2006. Among manufactures, the contribution of small and medium-sized enterprises (SMEs), which are the manufactures with less than 300 workers, was about 20 %. According to the 2006 PRTR investigation, the numbers of plants submitting the notification of emission were 24,412 plants of 0-20 workers, about 60 % to all, and 9,739 plants of 21-100 workers, about 24 % to all. It means that the emission sources are distributed to many companies as thin volume, which can be regarded as the factor of making it difficult to reduce the emission volume. Viable solutions for each process under individual constraints must be considered. As well as manufacturing industry, the restaurant, the service, the construction businesses, and residents, which are not targeted in PRTR investigation, have the potential of nonnegligible contribution to total emission volume. For an appropriate reduction of chemical risks, such emissions should be reduced totally, which necessitates the participation by all to play roles for risk control supervising chemical benefits. For generating economically-viable solutions appropriately, the best-mix of risk controls by laws, regulations, and voluntary managements should be implemented into actual decision makings.

As the many stakeholders can dominate chemical risks including environmental impacts, the researches have been conducted on various approaches for the reduction in chemical risks and the establishment of sustainability. Design for Environment (DfE) (ISO 2002) is one of the powerful concepts to integrate environmental aspects into product design and development. At the same time, process DfE was conceptually discussed (Cano-Ruiz 1998) as an approach in PSE. As well as the researches on industrial decision making on environment, those on environmentally conscious activities by other decision makers have been discussed. Environmental policy-making has a long history with risk assessments (Russell 1987). Sustainable consumption focuses on establishing a system enabling the effective satisfaction of human needs while simultaneously promoting equitable social development, economic competitiveness, and technological innovation (Oslo Declaration on Sustainable Consumption 2005). Although various researches were conducted and knowledge were cumulated, such results have not always been implemented into actual decision making appropriately. Because the problems of chemical risks and environmental impacts are related with multiple decision makers and the knowledge cumulated by these previous researches is not structured practically for decision making, structuration of knowledge on risk-based decision making is strongly needed for the sustainable risk control with supervising chemical benefits.

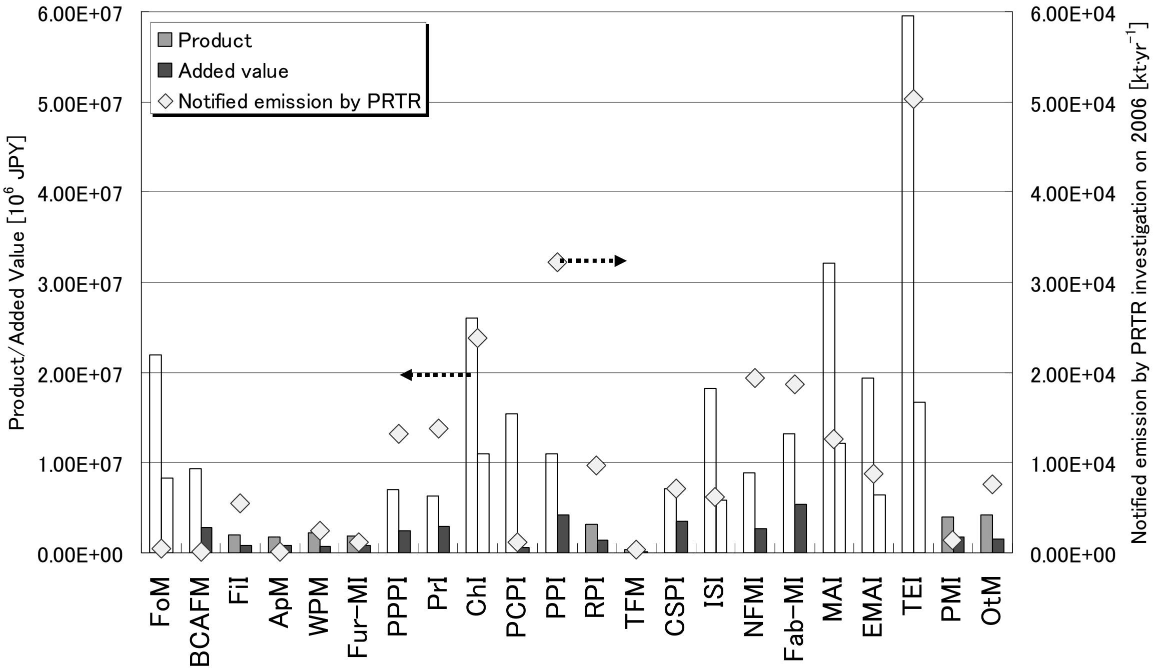


Figure 1-3 Manufacturing sector-based overview of the relationships among product, added value and notified emission by PRTR investigation on 2006.

(FoM: Food Manufacture, BCAFM: Beverage, Cigarettes, Animal Feed Manufacture, FiI: Fiber Industry (except Apparel, others Manufacture), ApM: Apparel, others Manufacture, WPM: Wood and its Product Manufacture (except Furniture), Fur-MI: Furniture Making Industry, PPPI: Pulp, Paper, Paper Converting Industry, PrI: Printing Industry, ChI: Chemical Industry, PCPI: Petroleum and Coal Products Industry, PPI: Plastic Products Industry, RPI: Rubber Products Industry, TFM: Tannage and Fur Manufacture, CSPI: Ceramic and Stone Products Industry, ISI: Iron and Steel Industry, NFMI: Non-Ferrous Metal Industry, Fab-MI: Fabricated Metal Industry, MAI: Machinery and Appliance Industry, EMAI: Electrical Machinery and Appliance Industry TEI: Transport Equipment Industry, PMI: Precision Machinery Industry, OtM: Other Manufacture)

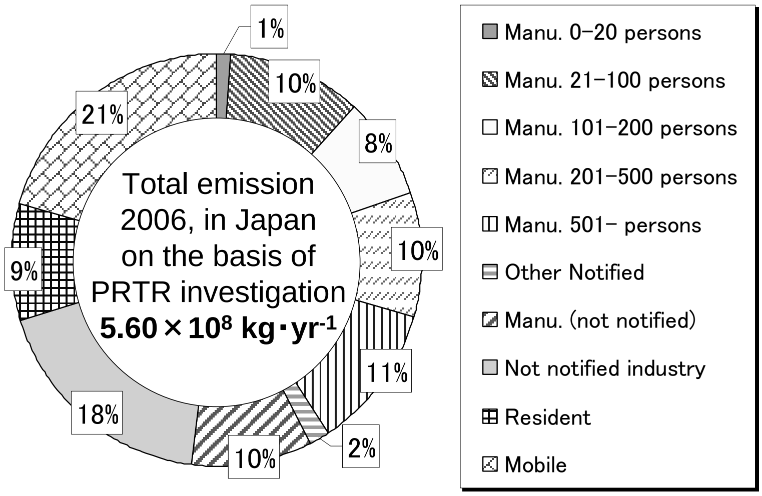


Figure 1-4 Contributions of each employer of chemicals to the results of PRTR investigation for the total emission in Japan 2006

1.2. Sustainable Process Design, Operation, and Management

Chemical engineering has successfully increased the efficiencies of energy and material uses in chemical plant productions. Such success can be regarded as the achievement by the remarkable development of PSE approaches, as well as the technology innovations. Chemical engineering has been able to divide the chemical production processes into unit operations (Duncan and Reimer 1998) and analyze them to establish process models with both empirical and theoretical knowledge, which enables systematic design and optimization (Bieglar et al. 1999) even in the early design phase in process development (Vogel 2005). On the basis of such systematic approaches in chemical engineering, or PSE, process development has been expanded to the sustainable development, especially to the reduction in EHS risks addressed at the early design phase.

Local risks, or microenvironmental risks, including occupational and neighborhood risks, must be supervised adequately by process engineers, because they have been considered as a constraint in management of processes utilizing chemicals. Such risks have been addressed by various types of risk assessment (RA) where risks are divided into EHS categories (Kolluru et al. 1996). EHS assessments at the early design phase of process development have been expected as the highly effective phase to reduce them in chemical plants, and methods for such evaluation have been developed (Koller 2000; Koller et al. 2000, 2001). As well as risks in plants, environmentally conscious process design has been discussed as an important issue in process systems engineering (Cano-Ruiz and McRae 1998). As life cycle assessment (LCA) has been developed on the basis of material flow analysis (ISO 1997, 1998, 2000a, 2000b), it became definitely a powerful tool enabling the quantification of regional/global environmental impacts attributable to the life cycle of products, from cradle to grave. LCA can also be regarded as a powerful evaluation tool in the early design phase (Hoffmann et al. 2001), and EHS indices should be objective functions in decisions related to process design and economic issues (Sugiyama 2007; Sugiyama et al. 2008b). In addition to developments in methodology, case studies of environmentally conscious process design have been performed (Shonnard and Hiew 2000; Kheawhom and Hirao 2004; Sugiyama et al. 2008b).

Although these developments and successes of chemical engineering can be firmly shared in various processes, it cannot be always applicable for all processes, especially open-system ones. Because almost all chemical processes are closed-system processes, mass and heat balance can be measured or estimated practically. Open-system processes such as machinery processes and metal processing have difficulties to implement such quantification. For such industries, PSE approaches should be implemented and systematic process modeling, design and operation should be addressed.

Figure 1-5 shows the interconnected products life cycles, where two kinds of risks are existing, process and product risks. Chemical products can be raw materials or process chemicals of end-products. As raw materials, metals are also the major materials from other industry. Machinery and metal processing apply these materials into products. At this time, chemical substances have the potential to cause chemical risks. Process chemicals cause local risks of processing plants, which can be referred as process risks. Such process risks include occupational health and safety issues and neighborhood problems. Additionally, raw materials cause the risks during the use of products and after waste treatments. Consumers' safety or health risks during use and the elution of hazardous substances from waste disposal sites are the examples of product risks.

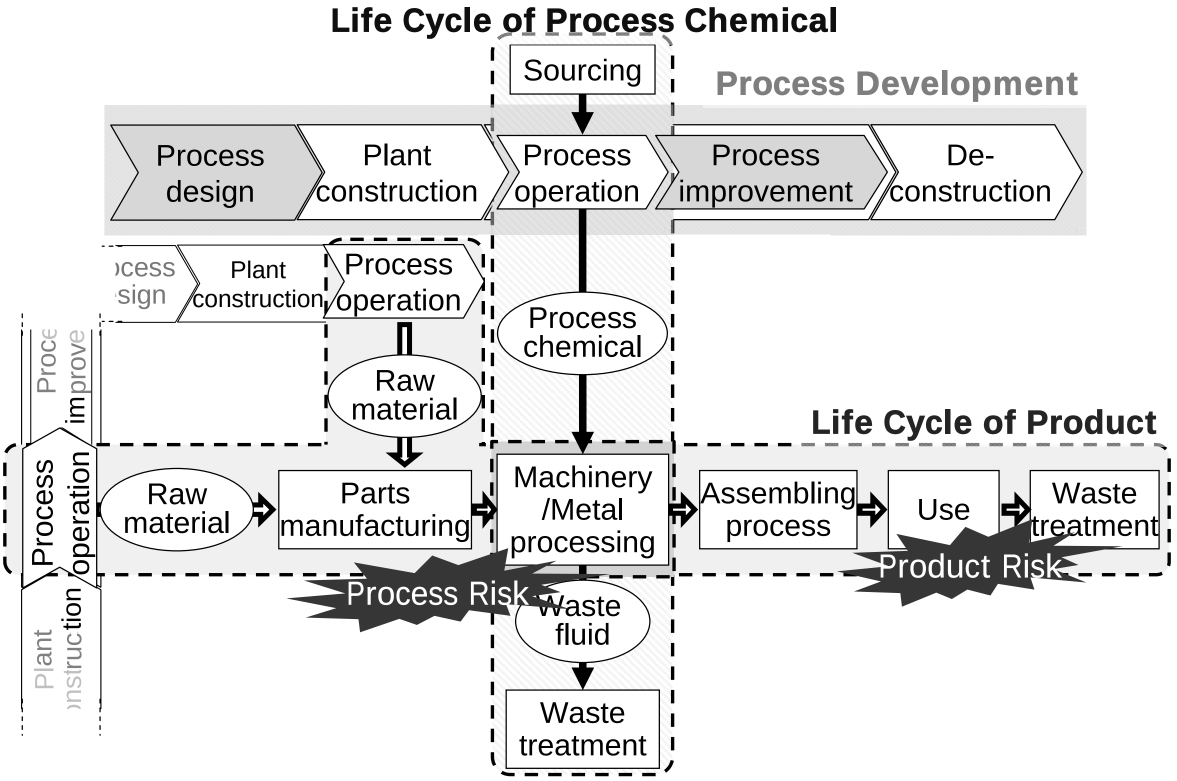


Figure 1-5 Process and product risks in the life cycle of process chemicals and products

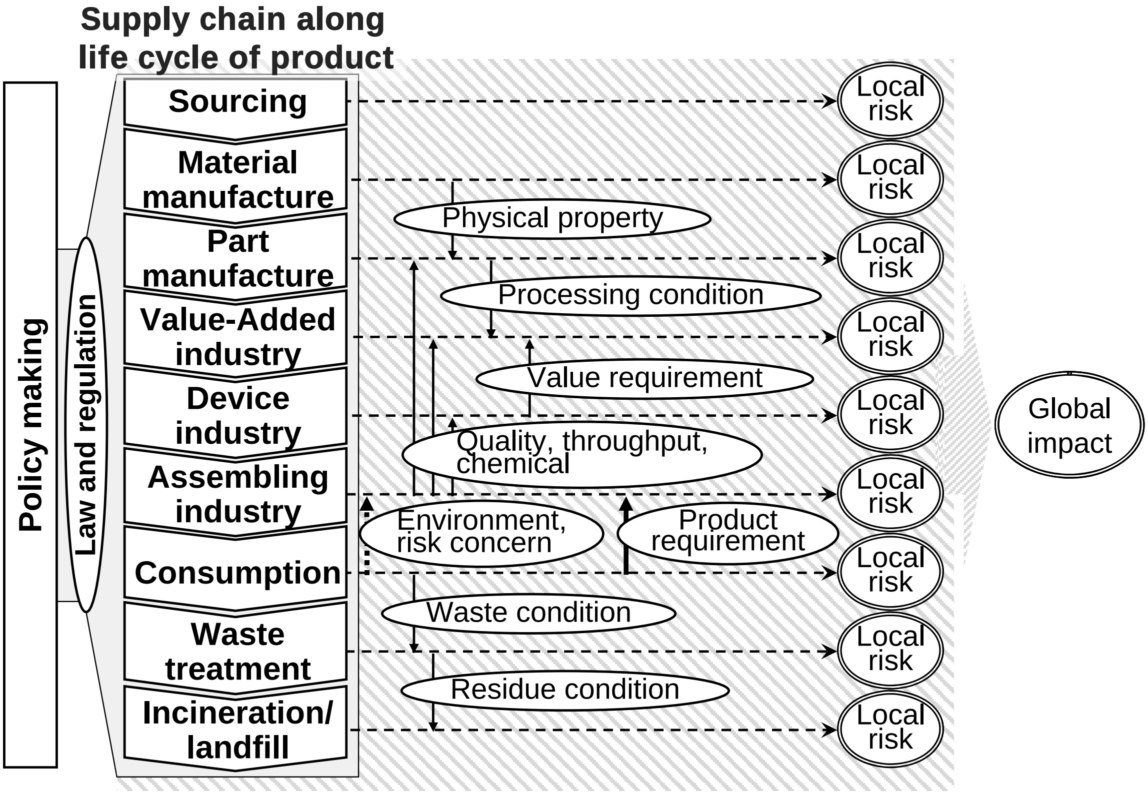


Figure 1-6 Local risks and global impacts originating from supply chain along the life cycle of product

Comparing the beginning of 20th century, when the chemical and other industries developed significantly, these risks could be reduced by technology innovations, optimization of processes at the process design and improvement phases under the legal controls. As shown in **Figure 1-3** and **Figure 1-4**, however, the chemical risks by low hazardous substances are the remaining problems, which are not only for chemical industry producing such chemicals, but also for other industries applying them. According to the PRTR investigation on 2006 emissions in Japan, the emission amount of discharging into the atmosphere has a dominant contribution to all, about 88 %, most of which are solvents utilized in almost industries as one of process chemicals.

Process chemicals and raw materials are selected on the basis of achieving process functions in each stage in a supply chain of a product. At that time, selected process chemicals cause local risks occurred around the site and ambient environment. Raw materials, meeting constrained product qualities, have a relationship with consumers' risks due to the failure modes and abnormal use of products and environmental risks at disposal sites. Simultaneously, as well as the emission of hazardous substances registered in laws and regulations as shown in **Figure 1-2**, the environmental loads including carbon dioxide might be emitted from the production of utilities in all stages in a supply chain, and cause global impacts, consequently. **Figure 1-6** shows such local risks and global impacts originating from a supply chain along the life cycle of products. In all stages, raw materials and process chemicals are utilized and such adverse effects are caused by the production of them and required utilities. A process should be designed, operated, and managed on the basis of concerning such negative aspects of chemical benefits. As well as process design including grass-root and retrofit designs, process improvement after plant construction as shown in **Figure 1-5** should be able to address such risk reductions.

For an appropriate process design and improvement, the process functions and constraints should be considered. **Figure 1-6** shows the flows of constraints among the stages of supply chain. Obviously, the consumption phase has a great power changing the all activities in a product life cycle. Assembling industry has also large potential to change the trends in local risks and global impacts. Sourcing and material manufacture seem to have no strong constraints from other stages. The stage under the most complicated constraints is the value-added industry, who must add the required values to received raw materials. There are many SMEs conducting such value-added manufacturing. They have high quality of processing materials to products, while simultaneously emitting a large amount of emission. In this regard, the processes in SMEs are not always adjusted to reduce such emission.

1.3. Toward Solving Problem on Risk-Based Decision Making

For the sustainable future, global impact and local risks due to the use of chemicals should be addressed in process management covering the planning, design, operation, and improvement phases of process development. Various constraints are imposed on decision making in industrial process design. Process management should focus on what chemicals or raw materials should be used under such constraints and how they should be applied. Alternative candidates, including the substitution of materials and the improvement of processes and operations should be generated on the basis of a sufficient understanding of the process system and its constraints. At this time, not a general solution but a plant-specific one should be addressed, because of the large variety and strong dependence of viable solutions on individual constraints with regard to actual process management. Chemical engineering, especially PSE has large potentials to analyze physical phenomena in processes, establish process models for simulation, and design a process considering specific objective functions by the process models. Such skill and knowledge have not been structured sufficiently to share with other industrial sectors. Knowledge sharing covers the development of sufficient solution for problem and the implementation of it into practice. For discussing this knowledge structuration, the following research needs might be the essential.

Research Need 1: Method of Structuring Process Evaluation Methodologies

RA is presented as a way of examining risks so that they may be better avoided, or otherwise managed (Wilson 1987). Various risk assessment tools have been developed and analyzed for prioritizing decision alternatives that effectively reduce both target and countervailing risks (Hofstetter 2002). Some of them were organized and discussed as the methods for EHS oriented and sustainable process design (Azapagic 2006; Sugiyama 2007). The evaluation methodologies discussed in the previous researches can be categorized to environmental and EHS risk assessment. As representative examples for them, LCA and RA should be considered.

Several approaches to the integration of RA and LCA, particularly life cycle impact assessment (LCIA), have previously been carried out. Under the OMNIITOX project, several discussions on the relationship between environmental RA and LCIA have been conducted (Molander et al. 2004). After OMNIITOX project, environmental RA employs a method of quantifying the environmental risks in a specific area in terms of a unit amount of emission (Larsen 2007). Additionally, LCIA for human health impacts has also been discussed previously (McKone 2006) including the implementation of indoor exposure assessment within the Task Force of the UNEP/SETAC Life Cycle Initiative (Hellweg et al. 2005; Jolliet et al. 2005). With regard to indoor issues, residential impacts have been discussed on the exposure models (Meijer 2005a, 2005b, 2006) and workers' impacts have been addressed in social LCA (Jørgensen 2008). The second version of the life cycle impact assessment method based on endpoint modeling (LIME2) (Research Center for Life Cycle Assessment 2007) includes the indoor exposure impact for a few number of chemical. These approaches aim to address local risks as one of the impact categories evaluated in LCIA.

For carrying out actual risk-based decision making, the method of assessing local and global impacts by separate applications of plant-specific RA and LCA should be proposed. In this approach, local risks and global impacts are evaluated separately by plant-specific RA and LCA. In contrary, a method of integrating local risks and global impacts can be accepted on the basis of the requirements at decision making. For more productive discussions on which approach should be applied for a specific decision-making situation, case studies must be conducted on actual decision making in the industrial setting.

Research Need 2: Knowledge for Risk-Based Decision Making

For making it practicable in process design to evaluate process by different assessment methodologies, related knowledge on process design and evaluation should be analyzed, systematized, and structured. The requirements are the knowledge on risk indices and indicators specification, alternative generation based on evaluation results, process simulation to estimate required process data for evaluations, and risk interpretation framework.

According to available assessment methodologies, there are various risk indices and indicators with different perspectives on risk by decision alternatives. A comprehensive analysis of all risks associated with them should be fulfilled. For 10 types of risks can be occurred by decisions: direct, upstream, downstream, accidental risks, occupational risks, risks due to offsetting behavior, change in disposable income, macro-economic changes, depletion of natural resources, and risks to the manmade environment (Hofstetter 2002). For appropriate assessment for making a decision, suitable indices should be concerned with the indication by adequate indicator, which has been discussed for impact categories and criteria selections in LCA (Hofstetter 1998; Seppälä 2002). On the basis of the perspectives of the evaluation indicators, decision makers should be able to select suitable indicators sets from available risk indices and indicators. In this time, the prioritization mechanism of available indices and indicators is strongly needed.

Evaluation results should be taken into account in generation of alternative candidate processes for the improvement of the target objective functions. At that time, alternatives should be able to relate with the evaluation results, which means the changed parameters of processes should have mathematical relations with the evaluation indicators, otherwise the alternative decisions cannot be compared. For such effective alternative generation, physical process models must be available. After generating alternatives, they must be assessed on specified risk indices and indicators. Process simulation for estimating required process data is inevitable in the process evaluation. Therefore, physical and mathematical process models should be developed for alternative generation and process simulation for the evaluation of candidates.

The perspectives of risk indices and indicators may have complicated meanings to understand simply for actual decision maker. Especially, the indicators for similar indices such as human health by acute and chronic toxicities by direct and indirect exposures may cause misunderstanding, and finally, not-intended decision making. In addition to the difficulty of physical understandings of indicators, evaluation may cause countervailing risk results, or trade-off relationships between results. For the sake of supporting decision maker, risk interpretation framework should be developed through the consideration of available decision methods.

Research Need 3: Business and Information Modelings for Enhancing Practicability of Risk-Based Decision Making

For the actual reduction of risk due to the use of chemicals under individual constraints, evaluations such as RA, LCA, and installation feasibility assessment should be practicable for each on-site decision maker. Activities and information assigned to a decision maker, which become massive and complicated, should be systematized to represent the way of collecting the required data, performing the evaluation, and interpreting the results as a clear procedure. The business modeling approach is useful for activating the smooth implementation of such new business activities (Naka 2006). Because the environmentally conscious design of processes needs systematically connected activities and information in process evaluation, simulation, and optimization (Chen and Shonnard 2004), effective support from information technology is important for process engineers (Schneider and Marquardt 2002) and also to apply the principles of industrial ecology (Heijungs et al. 2006; Capello et al. 2007, 2008). An activity model of risk-based decision making should be created as a basis for appropriate software system development, in order to show system requirements (Ajisaka 2008; Davis 2006; Havey 2006). The type-zero method of integrated definition language or IDEF0 (Ross 1985; NIST 1993) has been widely used in BPR (Killich et al. 1999). IDEF0 originating from a structured analysis and design technique (Ross 1977, Ross and Schoman 1977), and was practically developed for material supply management in the US Air Force (US Air Force 1974). IDEF0 accounts for a large share of modeling manufacturing processes (Skander et al. 2008), and visualizes requirements in software systems development with other modeling languages, especially unified modeling language (UML) (Kim et al. 2003; Theissen et al. 2008). As well as activity modeling conducted by IDEF0, information systems modeling is an essential requirement for the early stages in systems development life cycle (SDLC), especially in strategic developments (US House of Representatives 1999). UML (OMG 2008) for systems modeling has a large potential to visualize and clearly communicate the system/data requirements for software systems from design stages (Gao 2006; Kim 2003; Traoré 2004; Roberts Jr. 1998; Weidenhaupt 1998) to maintenance and sustainment stages (Arisholm 2006; Rugaber 2004).

In process design, several authors have applied this activity modeling approach to integrate new or existing engineering methods and tools for environmental protection including EHS risk control (Fuchino and Shimada 2003; Fuchino et al. 2004; Sugiyama et al. 2006; Gabber et al. 2004; Sugiyama et al. 2008a; Nakano and Hirao 2008). For the actual knowledge activation, combination of information systems and business models is necessary for actual decision makers in industries.

Research Need 4: Actual Case Study on Process Improvement

For the verification, certification, validation of risk-based decision making, actual case study should be performed. Industrial cleaning can be taken up as an actual case where significant amounts of chemicals are used. In an ordinary metal processing, metal parts are greased to avoid possible friction produced by pressing or cutting. The greased process oil and machining swarf are regarded as one of the impurities to be removed before following processes. Before sending metal parts to a subsequent process, a cleaning process for metal degreasing is inevitable. In such a cleaning process, however, various chemicals have been used as cleansing agents, and thus, their emissions to the environment and occupational impacts have frequently become a problem (MOEn 2007). Metal parts for precision instruments are required to be strictly cleaned, because the quality of products is highly sensitive to the remaining impurities. Chlorinated agents have widely been used because they can flexibly degrease various metal parts with complex shapes. With chlorinated agents, open-top washing machines have been utilized in many cleaning sites because of their high productivity. Recently, the use of chlorinated solvents has drawn attention as a cause of both green house effect gas (GHG) and volatile organic compound (VOC) emissions in Japan (MOEn 2007, 2008c). Although the installation of closed-loop washing machines could reduce such emissions in Germany (von Grote 2003), it is not a viable solution for all cleaning sites to install a sufficient number of closed-loop washing machines to maintain the throughputs of products. This is because the throughput of a closed-loop washing machine is generally lower than that of an open-top one and most of the cleaning sites in Japan are small and medium-sized enterprises (SMEs) or family-owned having severe restrictions on space and fund for investments. Some scenarios using trichloroethylene and an aqueous detergent were analyzed by LCA (ECSA 1996), which cannot easily be applied to the risk reduction in SMEs because the adoption of an aqueous process requires big capital investment and large space for waste water treatment.

1.4. Thesis Objectives

This dissertation presents the structuration of knowledge on process design and evaluation for risk-based decision making, where different assessment methodologies such as LCA and RA are appropriately applied on their perspectives and logically connected with business activities in practicable style. The risk-based decision making should be considered not only at the early design phase of process and project, but also at the process improvement phase. For activating such continuous improvements, the practicability of risk-based approaches should be enhanced sufficiently. The knowledge structuration enables the establishment of strong link among methodologies in different scientific fields such as life cycle engineering, chemical risk research, and PSE. As well as such interdisciplinary achievements, actual implementation of cumulated outcomes from scientific researches into practice can be fulfilled by logically and practically visualizing the use of knowledge as business and information models.

Followings are the required tasks and knowledge structures scoped in this dissertation.

- A method of associating different assessment methodologies on non-monetary issues including local risk and global impact.
- Risk specification method for selecting risk indices and indicators on the basis of scientifically- and practically-validated logic.
- Requirements definition of process modeling for alternative generation considering evaluation results within risk-based decision making.
- Business and information modelings for enhancing the practicability of risk-based decision making by on-site engineers.
- Implementation of risk-based decision making into an actual case for vilification and validation of knowledge structuration.
- Verification of the general applicability of proposed knowledge structuration

Based on this dissertation, the method of analyzing the knowledge on process design and evaluation can be proposed for practical implementation of them into business models.

1.5. Structure of Thesis

The structure of this dissertation is presented in **Figure 1-7**. After the introduction in **Chapter 1**, **Chapter 2** presents the concepts of knowledge structuration addressed in this dissertation. It is mainly the way of progressing knowledge structuration by integrating knowledge on process design and evaluation. Knowledge link to the activities requiring it and other knowledge to execute process design and evaluation. At the same time, **Chapter 2** presents a method of modeling such activity relation and information structure by applying IDEF and UML languages for logical visualization.

Chapter 3 presents the problem identification on actual case study of metal cleaning process. Based on the identified conditions, the scientific solution for the problem is developed as a novel method for process evaluation. To enhance the applicability of developed method, knowledge on process design is categorized into several semantic units to simplify the logical connections between existing and developed methods. **Chapter 4** introduces five categories of knowledge: mechanisms of risk specification (RSM), evaluation (EvM), alternative generation (AGM), process simulation (PSM), and risk interpretation (RIM). **Chapter 4** presents the developed methods of each category by analyzing and combining existing knowledge to create complementary styles. The developments of them are independently presented in sections 4-2 to 4-7, and consequently, mechanisms can be connected to a knowledge network for risk-based decision making, which can be shown as a pentacle in **Figure 1-7**.

Developed mechanism network has the logical connection of information with activity requiring each mechanism. **Chapter 5** works up the structure of business activity and information for risk-based decision making by IDEF0 and UML diagrams. IDEF0 model on the viewpoint of on-site engineers is presented in section 5-2, where the activity requires skill and knowledge on process design and evaluation. For the actual decision makers in industrial cleaning, knowledge on such activities is translated into more user-friendly style and the user and data/system requirements are defined by UML diagrams introduced in sections 5-3 and 5-4.

Chapter 6 discusses the general applicability of the knowledge structuration for risk-based decision making. This chapter introduces the difference of proposed structured knowledge on process design and evaluation from the PDCA cycle.

Chapter 7 concludes this thesis with recommendations for further studies on knowledge structuration. Risk-based decision making has been strongly needed in other decision making such as policy making and sustainable consumption. The knowledge network and method of integrating it with business activities have large potential to address such other issues. In **Chapter 7**, the required tasks in other issues to implement risk-base decision making are indicated.

This thesis includes **Appendixes** for the representation of detail results and resources. The results of process analysis, experimental settings and results are summarized for further discussion of process modeling. The overview of IDEF family and UML diagram is represented. Investigation results and utilized substance properties are also organized in **Appendixes**.

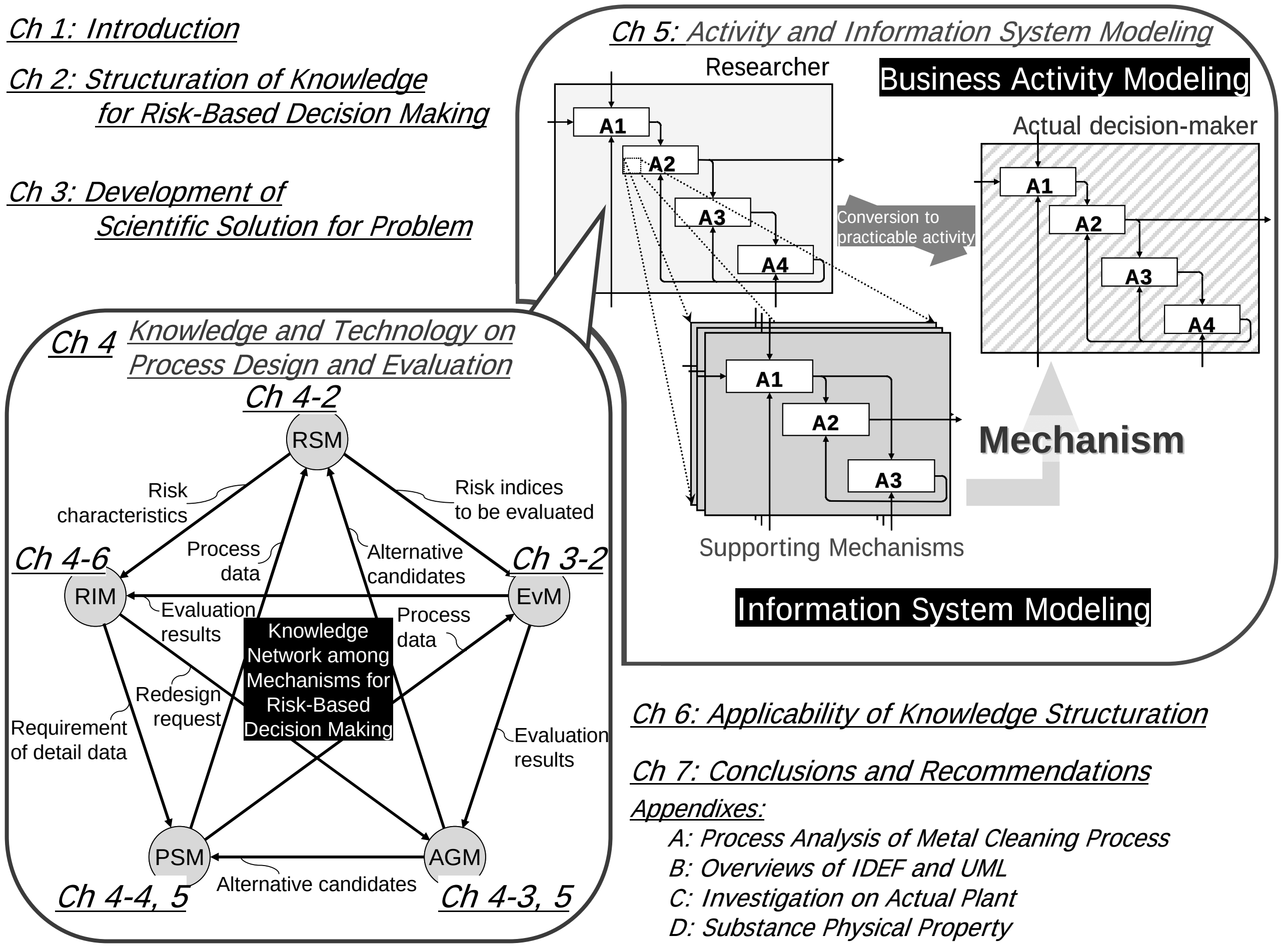


Figure 1-7 Structure of this Ph D thesis:
risk-based decision methods and structuration of knowledge

Chapter 2. Structuration of Knowledge for Risk-Based Decision Making

2.1. Concept of Knowledge Structuration

2.1.1. Introduction

Knowledge is the foundation of all technology, activities, and methodologies. Analyzing previous events and facts, or evidences, common theories have been established in many fields of study. Process design and evaluation have been developed simultaneously for the optimization of process parameters based on objective functions. Process systems engineering (PSE) and computer-aided process engineering (CAPE) have successfully developed systematic method of designing chemical process (Biegler 1997; Duncan and Reimer 1998). In this regard, however, the most of considered objective functions have been related with monetary issues, which can easily link to process input/output. As the environmental impact and EHS risk had become nonnegligible issues, the implementation of such non-monetary issues into objective functions has been necessitated strongly. Although it means that LCA and RA should be applied into process design, such methodologies have been developed in different field of study. Knowledge structuration logically and practically connecting process design and evaluation should be addressed and achieved for risk-based decision making in process design.

2.1.2. Knowledge Conversion

Empirical knowledge is the foundation of empirical rules that have been developed and accumulated in industries based on the previous repetitions of specific experiences and experiments. As well as industries, other organization also accumulated such knowledge as evidences. Because such knowledge supposes the peculiar conditions of specific events, it can be immediately executable by decision maker. For implementing novel knowledge from other fields, empirical knowledge can be a milestone to convert the general knowledge into specifically applicable one. Knowledge structuration is started at the reasoning analysis of empirical knowledge.

Figure 2-1 shows the knowledge structuration circulating knowledge conversion. **Table 2-1** and **Table 2-2** organize the terminology within the knowledge conversion process shown in **Figure 2-1**. Evidences in practices can be converted into formalized knowledge such as figures, tables, and mathematical equations. Accumulating and associating them, formalized knowledge can be systematized, which can be connected with other systematized one from other field of study. This combination of systematized knowledge is defined to establish structured knowledge. Structured knowledge cannot be useful unless it can be applicable in actual business model. In order to enhance the applicability of structured knowledge, business model is developed and knowledge is converted into practical knowledge with developed business model. Practical knowledge includes the connection with actual procedure of business activity. It can become practicable for actual decision maker by activation by mechanisms. When other problems are identified during the utilization of practicable knowledge, the knowledge conversion cycle will start again based on the new evidences.

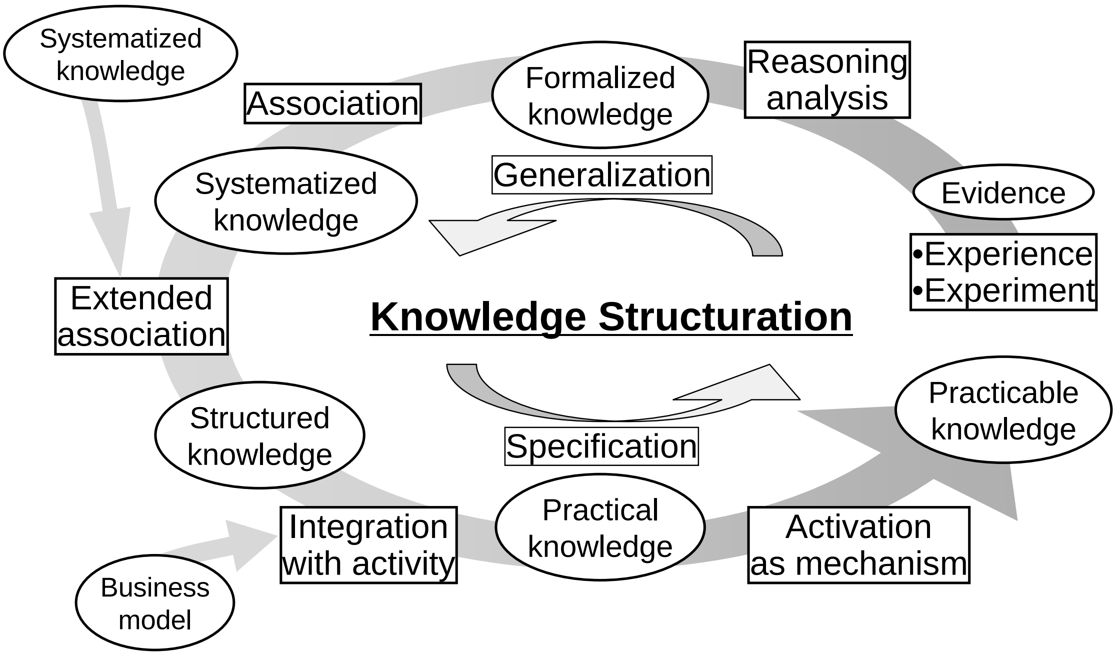


Figure 2-1 Knowledge structuration circulating knowledge conversion

This knowledge circulation might be conceptually general in all fields of study, Converted and obtained practicable knowledge enable new experiences and experimental ideas, and then novel evidences can be found. This repetition has enabled the development of science. The implementation of risk-based decision making can be regarded as required knowledge on process design and evaluation is associated and integrated with actual business model.

Table 2-1 Terminology on knowledge conversion process in knowledge structuration

	Dictionary meaning	Definition in this study
Experience/ experiment (Generalization)	(Experience) practical contact with and observation of facts or events (Experiment) a scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact	Trials of the application of methods including theoretical and empirical ones
Reasoning analysis (Generalization)	(Reason) think, understand, and form judgments logically	Analysis and acquisition of the rationales behind evidences and the logics of the occurrence of them
Association (Generalization)	(Associate) connect or involve with something else because they occur together or one products the other	Combination of formalized knowledge within certain knowledge classification which can be identified by the requirements of knowledge for solving problems on decision making
Extended association (Generalization for specification)	(Extend) cause to cover a wider area; make larger	Combination of multiple categories of systematized knowledge for integration with actual activities in business model
Integration with activity (Specification)	(Integrate) combine with another to form a whole	Logically connection of systematized knowledge with actual activities on decision making
Activation as mechanism (Specification)	(Activation) make active or operative (Mechanism) a system of parts working together in a machine; a piece of machinery; a natural or established process by which something takes place or is brought about	Enhancement of the practicability and applicability of knowledge for business model, especially for actual decision maker
Knowledge structuration	(Structuration) the state or process of organization in structured form	Knowledge conversion cycle including generalization and specification

Table 2-2 Terminology on converted knowledge in knowledge structuration

	Dictionary meaning	Definition in this study
Evidence	(Evidence) the available body of facts or information indicating whether a belief or proposition is true or valid	The smallest unit of knowledge and logic derived from experience or experiment, which can be represented as fact
Formalized knowledge	(Formalize) give a definite structure or shape to	Knowledge and logic represented by qualitative and quantitative style, including illustration and equation, which combine multiple evidences
Systematized knowledge	(Systematize) arrange according to an organized system; make systematic	A methodology established for a category of knowledge on decision making
Structured knowledge	(Structure) construct or arrange according to a plan; give a pattern or organization to	A method combining methodologies in multiple categories of knowledge on decision making
Practical knowledge	(Practical) of or concerned with the actual doing or use of something rather than theory and ideas	Converted knowledge from scientifically- and logically-defined methodologies into actual procedures concerning business model
Practicable knowledge	(Practicable) able to be done or put into practice successfully	Tool or other mechanisms, into which knowledge is implemented and converted

2.1.3. Logical Knowledge Connection for Generalization

Knowledge generalization should be able to involve all related evidences, facts, physical logics, techniques, and knowledge. Because the premise of each type of knowledge is different, such structuration should be quantified and validated by unified recognition concepts. This subsection discusses the conceptual structures of knowledge, which shows the overview of reasoning analysis, association, its expansion of theoretical and empirical knowledge, and the general framework of structured knowledge.

Figure 2-2 shows the overview of empirical knowledge. Empirical knowledge has a high applicability for problems under specific conditions. This is one of the reasons why heuristics has widely been utilized in various engineering fields. This also means limited application range of such knowledge, because the premises of empirical methods are not always same as those of problems under real situations. Additionally, it is not doubtful that non-experienced problems cannot be solved by empirical knowledge. There is an obvious limitation of the range of problems solved by independent knowledge.

Knowledge structuration establishes the connections among independent knowledge for enabling flexible and systematic application of them. Empirical knowledge has the attributions regarding the case-specific conditions. To connect such knowledge existing as instances, conversions by a kind of generalization must be necessary. It is to reason empirical knowledge and acquire the rationale of it. **Figure 2-3** shows the combination of empirical knowledge by connecting the acquired rationales of it. **Table 2-3** organizes the synopsis of formatting such combination. Rationale is the logical reason validating the applicability and exactitude of empirical knowledge on specific conditions.

Although rationale of empirical knowledge, in other words heuristics, must exist, a large number of it have not be clarified logically, because the reasoning of empirical knowledge was not always needed. Even if an empirical knowledge has no clear rationale, it will work under the appropriate conditions, which would be recognized and adjusted by skilled on-site engineers. Rationales required for knowledge structuration should be revealed by scientific analyses; induction/reasoning as function “Why so?” and deduction as “So what?”. The set of "why so?" and "so what?" has been proposed in training logical thinking and speaking skills (Teruya and Okada 2001).

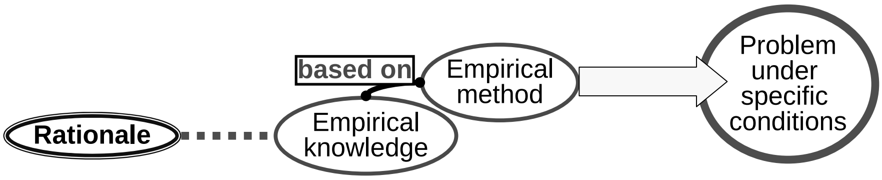


Figure 2-2 Rationale behind empirical knowledge

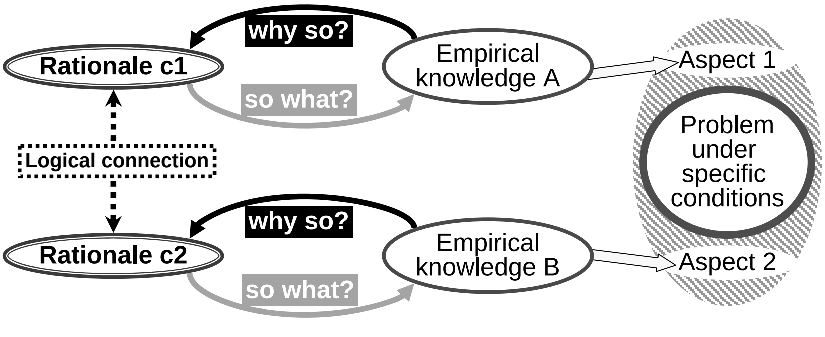


Figure 2-3 Combination of empirical knowledge by logical connection

Table 2-3 Synopsis format of structuration

Empirical knowledge	Description of real situation
	If-then statement of phenomenon
	If-then statement of operating
Rationale	Cause of if-then statement
	Missed logical connection of physical phenomenon
	Scientific interpretation of empirical knowledge
Why so?	Scientific reasoning seeking relation “A is reasoned by B”
	Scientific induction seeking relation “A is scientifically interpreted as B”
So what?	Scientific deduction seeking relation “A causes B”
Logical connection	Logical connection based on scientific relative analysis between A and B

In **Figure 2-3**, the rationales of two different units of empirical knowledge are logically connected as “Aspect (Asp) 1 is explained by empirical knowledge (EK) A. EK A is reasoned by Rationale (R) c1. R c1 is related with R c2. Therefore, EK A and B structured and Asp 1 and 2 may relate each other”. In this way, empirical knowledge, which is seemingly without logical connection, can connect each other on a specific meaning. Such connection has various types of the logical conjunctions.

In **Figure 2-4**, logical connections are shown as parallel and series of rationales. Empirical knowledge has multiple different rationales, which depends on the way to obtain them. In order to declare and organize the way to obtain rationales, a conceptual item "category for reservoir of rationales" should be prepared. Category is defined as a coherent semantic unit for physical phenomenon or for chemical risk in this research. In **Figure 2-4**, the empirical knowledge A and B have rationales in category α. An example can be addressed on heat transfer. If the empirical knowledge A and B are on heat fluid temperature and velocity, respectively, the category α including rationales a1 and b should mean Fourier equation (SCEJ 1999). In this time, the rationale b is heat transfer coefficient, and then, the rationale b' can be the Reynolds number at the fluid velocity. Category γ can be the dependency of heat transfer coefficient on physical dimensionless parameters such as the Reynolds, Nusselt, and Prandtl numbers (SCEJ 1999). Rationale c can be a physical parameter related with such dimensionless numbers.

Through such analyses on the empirical knowledge, knowledge can be logically connected. At the same time, the aspects related with each empirical knowledge are structured and related on a problem.

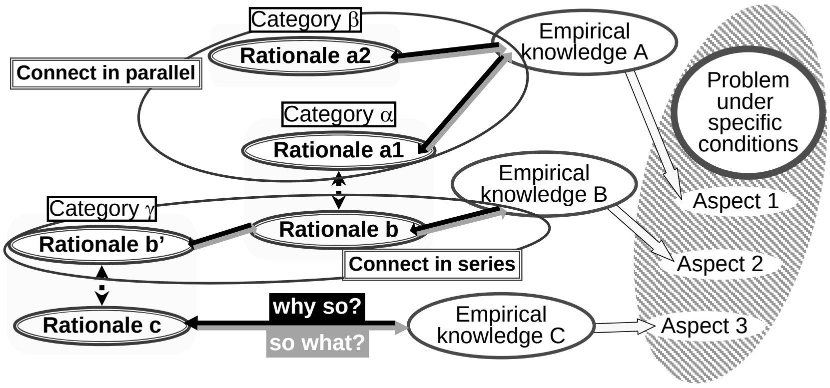


Figure 2-4 Category to integrate the rationales behind empirical knowledge

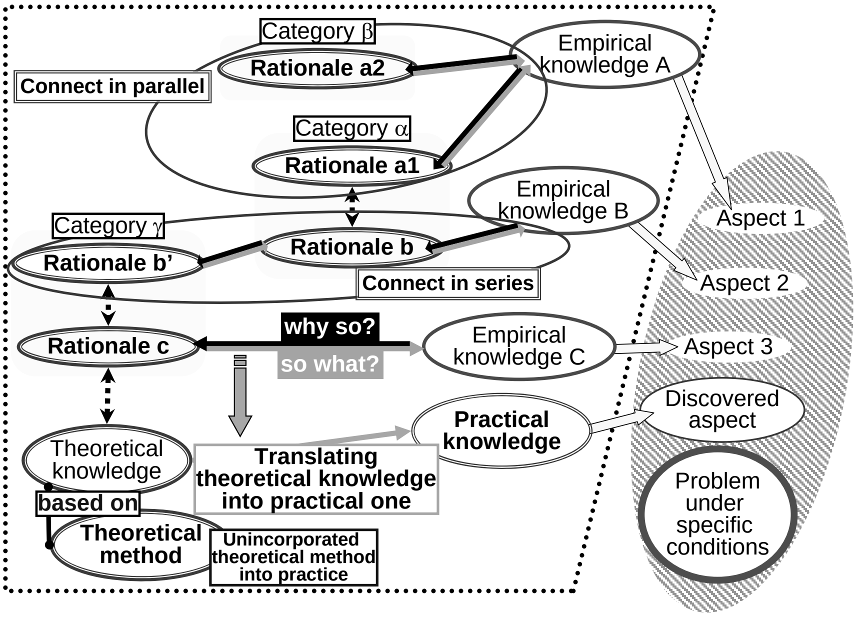


Figure 2-5 Knowledge structure by logical tree linkage

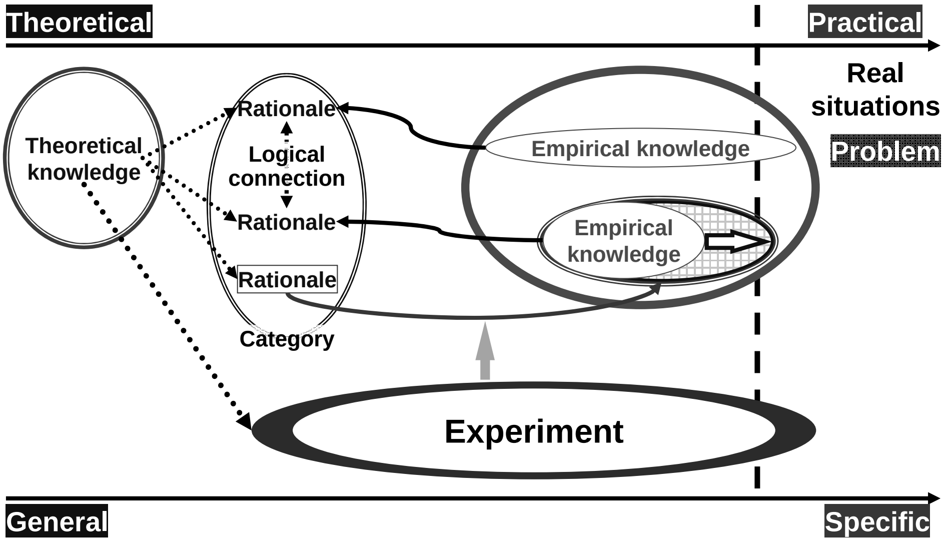
As mentioned above, logical grounds and varieties of empirical knowledge can be analyzed and organized. In **Figure 2-4**, mutual connections among knowledge become visible as a logical structure. It means that an integrated method can be available by connecting empirical knowledge. Theoretical methods and knowledge are unincorporated into practice on industry, because the logic of them is not clearly suitable for actual situations in industrial decision making. Such knowledge needs translation of them into practical use case. This research proposes such translation as the way to integrate and convert unincorporated theoretical knowledge into practical one by applying the embodiment technique for logical connection: collaboration of "why so?" and "so what?".

Figure 2-5 shows the knowledge structure by logical tree linkages including empirical knowledge and unincorporated theoretical knowledge. The requirements of theoretical knowledge for implementing it into practice can be identified through connecting rationales behind empirical knowledge. Based on the requirements, theoretical knowledge might be converted into practical knowledge on site. Such acquired practical knowledge from theoretical one can discover unknown aspects of problems, which would lead to provide novel solutions for them.

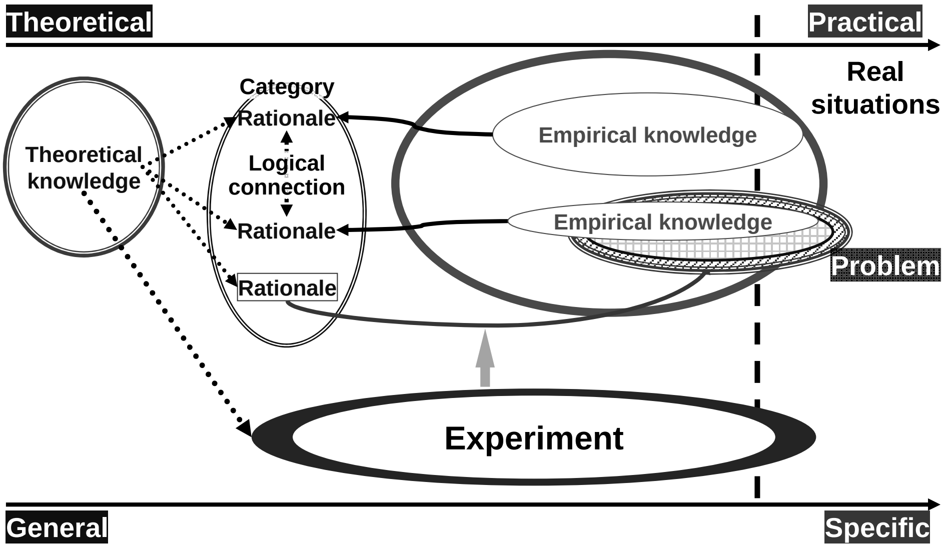
Many scientific methods on non-monetary issues, such as LCA and RA, have been far behind from the clearly-connected knowledge in practice. Although such methods can reveal various aspects of process systems, actual procedures of them have not been implemented in industrial decision making. On the other hand, industries have performed original process systems analyses, which enables them to clarify original understandings on qualities, requirements, and conditions of their own process systems. If the empirical knowledge by these analyses is connected with novel methods, the implementation might become considerably easier and more practical. Knowledge structure overviewed in **Figure 2-5** should be an essence and a concept of integrating technology, knowledge, and actual decision making.

Structuration Patterns

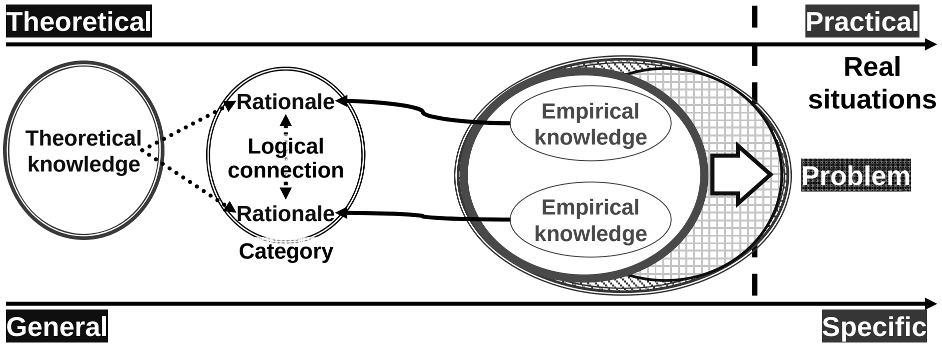
Structuring theoretical knowledge with the systematized knowledge from existing empirical knowledge as shown in **Figure 2-1**, three patterns of structuration of knowledge are possible, which are shown in **Figure 2-6**. In **Figure 2-6**, rationales behind empirical knowledge can be connected with new rationales by specifying categories. They are related with the same theoretical knowledge as that of rationales from empirical knowledge. New rationale can be structured with empirical knowledge on the basis of verification and validation analysis, which is experiment in **Figure 2-6**. At this time, there are three patterns of structuration. **Figure 2-6**-(a) shows the case that empirical knowledge, which has not been able to deal with problems, can be corrected by new rationale. **Figure 2-6**-(b) shows that the solvable range of empirical knowledge is expanded by new rationale. In these two cases, empirical knowledge has been able to solve the problem to some degree. The correction and enhancement of knowledge are the main target. The case shown in **Figure 2-6**-(c) is different from the previous two cases, where any empirical knowledge cannot tackle problems directly. Environmental impact from the life cycle of products can be an example. For such situation, the new rationales from theoretical knowledge, e.g., LCA, should be implemented and can be a solution for problems by structuring it based on related empirical knowledge and experiment.



(a) Correction of empirical knowledge



(b) Enhancement of empirical knowledge



(c) Expansion of empirical knowledge

Figure 2-6 Structuration of theoretical and empirical knowledge

2.1.4. Specification of Structured Knowledge

In the previous section, the generalization of knowledge in **Figure 2-1** is introduced as the linkage creation between knowledge with logical connections. Based on the generalization, the knowledge systematized on multiple fields can be logically connected as a structure of knowledge. For the conversion of such knowledge into practicable one, integration with business model and activation by mechanism are discussed in the followings.

Knowledge Integration with Business Model

All engineering knowledge has the premises under which it can be effective for tackling problems. The premises include the situations and constraints of activities of decision makers. For making adequate knowledge referable at specific conditions during risk-based decision making, actual business modeling must be powerful approach. In the modeling, the definition of information required for the accomplishment of activity becomes an important point to integrate knowledge appropriately.

Knowledge Activation as Supporting Mechanism

Even if adequate knowledge can be available in activities, decision makers may sometimes fail to fulfill it appropriately. This is because they cannot apply the available knowledge for their own activities due to the lack of knowledge for, skill of, and experience on the application. For the practical activation of practical knowledge, the style of providing knowledge should be considered carefully.

For sharing knowledge, various activation media can be possible such as scientific journals, books, web pages, and software tools. If the decision makers to utilize knowledge are researchers, scientific journals and books are sufficiently effective as activation media. In most of actual decision making for risk reduction, however, those who should be able to apply knowledge are industrial engineers including on-site engineers. They may have difficulties to understand and implement the knowledge represented as scientific journals and books into their own activities. For them, customized software information system has a strong potential to share knowledge with such decision makers. Software system can cover the lack of their techniques to apply the knowledge into practice. Especially, graphical user interface (GUI) plays a role of simplifying the application of knowledge into practice. The role of GUI is to act as an intermediary between the decision makers and other unit mechanisms on risk-based decision making, which are reservoir of structured knowledge.

2.1.5. Application into Actual Problem

Problem on decision-making has been addressed along with the phase shown in **Figure 2-7**. At first, the various and detail aspects of problem must be identified carefully. Based on the identified characteristics of problem, the solution might be developed. Then, the developed knowledge is published through journal papers or literatures. The publication may stimulate the application and implementation of knowledge into practice. Usually, researchers develop the solution for problem and publish the achievement of research. The actual application and implementation are carried out by other researchers, actual decision-makers, or consultation engineers, who can understand the knowledge from published resources.

Proposed knowledge structuration aims to solve the problem on risk-based decision-making. The stages in the phase of solving problem involve the all related players such as researchers, decision-makers, and system engineers for actual implementation.

Figure 2-8 organizes the activation of integrated knowledge through the GUI of software system. The practical knowledge can include the integrated one, which are constructed with business model and structured knowledge. Structured knowledge is based on scientific knowledge such as LCA and RA. This means that the software system with adequate GUI enable the users to fulfill activities indirectly based on such assessment methodologies. Software systems development can be regarded as the important activation of knowledge to implement structured knowledge into practice.

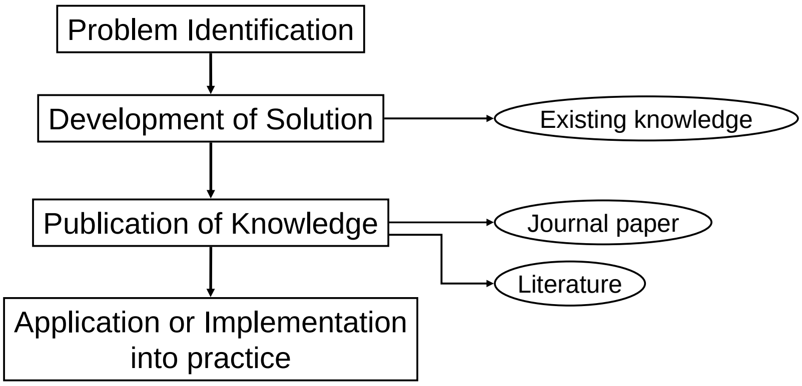


Figure 2-7 Phase of Solving Problem on Risk-Based Decision Making

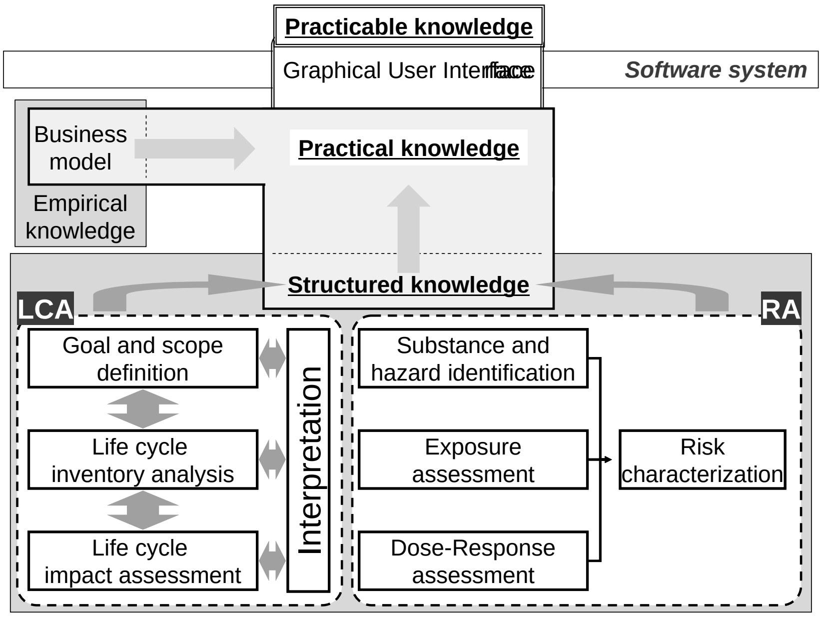


Figure 2-8 Activation of integrated knowledge through GUI of software system

2.2. Knowledge Integration and Activation in Decision Making

2.2.1. Introduction

Risk-based decision making requires comprehensive integration of knowledge into a decision. There are various types of knowledge developed in actual operations on site and research activities. All knowledge is developed to solve certain problem and to reveal unknown fact. Logical analysis and understanding are needed to apply knowledge into a problem different from original. Chemical risks including environmental impact and local risk are recent problems, which are strongly related with process system operated during several decades. Acquired knowledge on process system must be an inevitable component for risk-based decision making. For the structuration of knowledge combining novel and time-cultivated one, conceptual structure should be addressed toward the establishment of meaningful connection among them.

Scientific and engineering knowledge surrounding chemical risk and benefit have covered a lot of ground and become complicated each other. Several researches have been able to demonstrate practical countermeasures against specific case problems with their proposed methods. Nevertheless, the explosion of the number of developed methodologies for environmental protection and risk reduction in process system has revealed the limitation of human capability to apply an effective and suitable one for a problem. This is because the decision makers are not researchers in such field. It is required that the researchers' capability can be shared among decision makers.

Computer system can search information corresponding with specific conditions from a vast trove of it. Such system can redeem the incapability of human to accomplish iterations of simple works. The high accomplishment of computer system can become an important keystone in risk-based decision making implementing state-of-the-art knowledge. For activities requiring comprehensive judgments, however, computer system cannot show a validate performance. For such activities, the intellectual activity by human is inevitable to compass a situation from all available viewpoints, and make a decision finally. A collaboration of human intellectual activities and computer system must be a solution for practicing risk-based decision making.

2.2.2. Applicable Modeling Languages, IDEF and UML

Logically connected knowledge requires suitable mechanisms in actual business models for becoming appropriately practicable implementation of it. Activities and information are assigned to decision makers, researchers, who establish and develop such logical connection and knowledge, and system developers, who can activate the support of the practicable implementation by software system.

Business modeling approach is useful to activate a smooth implementation of new business activities (Naka 2006). Because environmentally-conscious design of processes needs systematically connected activities and information in process evaluation, simulation and optimization (Chen 2004), effective information technology support is important for process engineers (Schneider 2002) and to activate industrial ecology (Heijungs 2006; Capello 2007, 2008). Activity model of risk-based decision as a business model should be created for the foundation of adequate software systems development to show system requirements (Ajisaka 2008; Davis 2006; Havey 2006). The type-zero method of integrated definition language or IDEF0 (Ross 1985; NIST 1993) have widely been used for business process reengineering filed (Killich 1999). IDEF0 was originating from structured analysis and design technique (Ross 1977a, 1977b), and practically developed in the material supply management in the US Air Force (US Air Force 1974). IDEF0 has accounted for a share of modeling manufacturing processes (Skander 2008), requirements in software systems development with other modeling languages (Kim 2003; Theißen 2008). In process design field, several authors applied this activity modeling approach to integrate new or existing engineering methods and tools for environmental protection and EHS risks (Fuchino 2003; Fuchino 2004; Sugiyama 2006; Gabber 2004; Sugiyama 2008).

As well as activity modeling conducted by IDEF0, information systems modeling is an essential requirement for the early stages in systems development life cycle (SDLC), especially in strategic developments (U. S. House of Representatives 1999). Unified Modeling Language (UML) (OMG 2008) for systems modeling has a large potential to visualize and clearly communicate the system/data requirements for software systems from design stages (Gao 2006; Kim 2003; Traoré 2004; Roberts Jr. 1998; Weidenhaupt 1998) to maintenance and sustainment stages (Arisholm 2006; Rugaber 2004).

2.2.3. Effective Software Development

To achieve a successful software development project, transparent and understandable users' requirements are inevitable (Procaccino 2006), which can be fulfilled by adequate development of communicable models and external consultation supports (Roberts Jr. 1998). Requirements from users can be the most important constraints on software development project (Davis 2006) and may cause the factors of software development risks (Ropponen 2000).

Risk-based decision might be a novel design policy for ordinary decision makers and system developers. It means that they do not have enough knowledge on the adequate business model and sufficient information. Those who have sufficient knowledge on risk-based decision are definitely researchers on it. The knowledge transferring from them to actual decision makers might need the support of software/information systems as shown in **Figure 2-9**. The knowledge of researchers is transferred through problem identification and requirements definition as IDEF and UML models, and then, such models can help the development of systems based on the knowledge by system developers. At this time, researchers can be a strong consultants of software developments to certificate the system functionality. Such collaboration among researchers and system developers for solving actual problem should be discussed in detail.

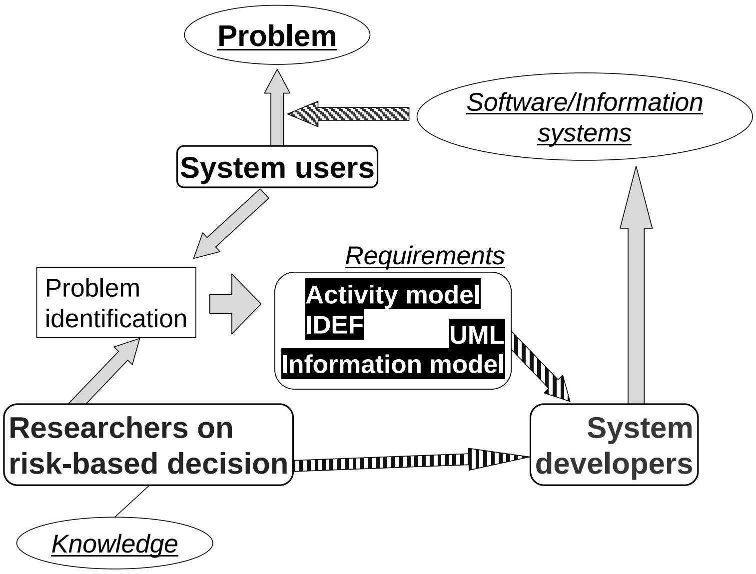


Figure 2-9 System development phases with the relationship with players: system developer, system user, and researcher

2.2.4. Software Systems Development Involving Researcher

Non-monetary issues, including local risk and environmental impact, tend to be regarded as additional tasks for actual decision-makers. To make it practicable for them to deal with such issues, case-specific discussions on risk-based decision should be engaged. The important action is to let them figure out the risk factors originating from their regular activities. Environmentally conscious and local-risk-friendly design and operation of process need the sufficient understanding of actual business model by researchers for an appropriate and practical application of scientific methods.

Such design and operation requires cumbersome data treatments; for example, process inventory management, life cycle data collection, and technical calculation. Therefore, information technology has a great potential to activate risk-based decision making. In this regard, however, almost information, is usually the cumulated data on site such as procurement, operation information and production. Data dealing is what usual decision maker has difficulties to do and information system can support. As well as the strong potential as a support, a rapid update or upgrade function to state-of-the-art technology is one of the largest reasons of the motivations to implement information technology.

General software tool has difficulties to become common among various industrial sectors, because the business models are completely different each other. The development of suitable software tool needs customization of data acquisition, calculation mechanism and GUI. Additionally, several researches on risk-based decision making have been developed in a couple of decades. They could have solved actual problems based on tactful application of environmental management methodologies by researchers. To enhance the efficiency and practicability of risk-based decision, such research achievements should be generalized and shared systematically enough to implement them into other fields and sectors.

The important players to accomplish systems development enabling such systematization must be system users, system developers, and researchers on risk-based decision making. The first two players are necessary for implementing software systems into actual business activities. The last one is the key player to achieve the implementation of risk-based decision into practice. **Table 2-4** organizes the roles of players related with software system development for support of risk-based decision making.

As organized in **Table 2-4**, risk-based decision is an inexperienced activity for system users and developers. Especially in state-of-the-art scientific methods, the researchers in the field are the only player who is familiar with the detail procedure of them. This means that the role of customizing such scientific methods should be assigned to the researchers.

Figure 2-10 shows the activity mapping of each player and the relations with software systems development. This map is composed of the regular activities for three players in their businesses. The requirement is to specify the collaborated procedure for appropriate systems development. In **Figure 2-10**, such activities grouped in the center. Additionally, some activities are over the borders of each player, which should have already been regarded as the activities to be collaborated. Activity and information models, IDEF and UML languages can visualize respectively, can behave interfaces among players to share knowledge.

Case study by researchers can develop the practices on risk-based decision for a specific case. The practices involved actual decision maker and based on individual conditions. IDEF0 activity model should and can be established in such case studies. Moreover, UML information model can also be developed on the basis of the analysis of verifying or validating risk-based decision methodology by the case studies.

Table 2-4 Roles of players related with software system development for support of risk-based decision making

Player	Researcher	System developer	System user
Ability and knowledge	•Development of scientific method •Enhancement and integration of state-of-the-art methodology	•Design and development of software system	•Detail understanding actual business procedure and process
Problem in ordinary system development	•Impracticability of complete system development •Incomplete implementation into actual business model	•Strong dependent of efficiency and utilization rate and duration on software requirements •Incomplete understanding of business model and scientific method	•Lack of knowledge on software system development and scientific research
Role in proposed system development	•Customization of scientific method on actual business conditions •Support of early system development phase	•Writing down the researchers' request •Development of system based on the requirements from researchers	•Specification of practicable activities and available information •Collaboration with researcher at software requirements definition

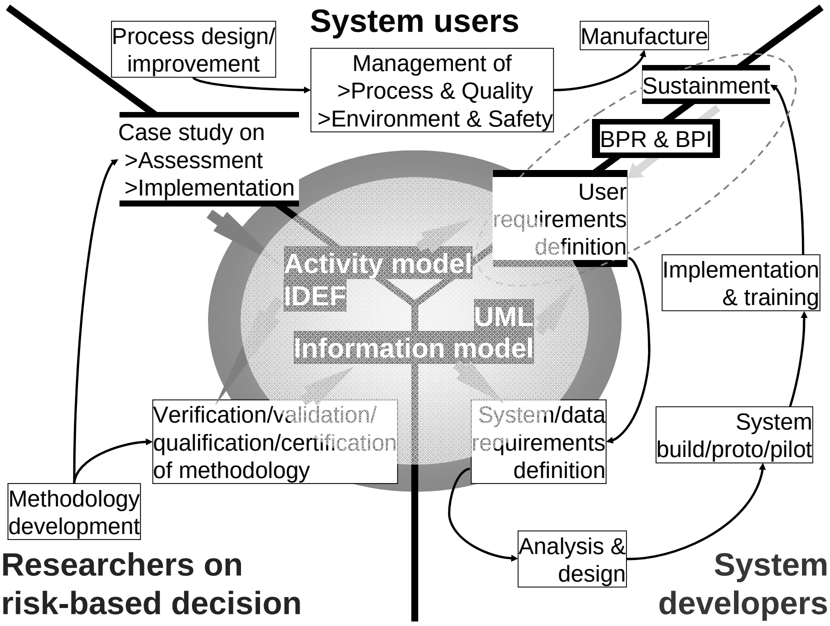


Figure 2-10 Activities of each player and their relations with software system development

Based on established IDEF and UML models, system developers can perform highly effective requirements definitions and sustainment including BPR and BPI. This is also beneficial for system users, because the IDEF and UML model, system users and developers must develop something like in requirements engineering, have high performance on implementing risk-based decision by involving researchers. Basing environmental management system on IDEF and UML can lead to effective sustainment of software systems, which are easily modifiable for improvement.

The developments of IDEF and UML models require a reasonable knowledge on business and software systems. Because researchers should be absolutely defined as ones of PSE or LCE, they have a limited capacity to develop such models for systems development. The assignment to them should be defined carefully and discussed on the actual procedure of a project solving a problem on risk-based decision.

2.2.5. Summarization

This chapter presents the conceptual analysis of knowledge structuration for risk-based decision making and practical modeling methods simultaneously applying IDEF and UML to visualize a business model with structured knowledge. For a practical implementation of risk-based decision making, the procedure for such decision should be take into account to business model. IDEF methods can visualize a business model, which has been natural language, as logically semi-formal language along with the modeling rule of IDEF. Based on the semi-formal visualization, a business model can be shared among stakeholders and researchers as developed IDEF model is a communication model. Although IDEF models can play a role as BPR for human intellectual activities, knowledge on risk-based decision making cannot be structured sufficiently. UML has become an effective language to visualize the specification of a computer system: for example, functions, modules connection, components and so on. This is useful in requirements engineering in software development, and applicable for the design of system actualizing knowledge structuration.

As decision makers in industries and system developers cannot sufficiently obtain the knowledge on state-of-the-art scientific methodologies, researchers have a important role to define appropriate requirements for software systems. It requires that researchers perform the adequate requirements definition of system achieving scientific methods by IDEF and UML. The case study of such modelings is introduced in Chapter 5.

Chapter 3. Development of Scientific Solution for Problem

3.1. Problem Identification in Metal Cleaning Process

3.1.1. Background

Cleaning means the process removing impurities from targeted products including clothes, dishes, metal parts, and devices installed in chemical plants (Committee of over viewing novel industrial cleaning technology 1996; JICC 2005). This process is included in industrial and consumer activities. Especially for industries, cleaning has a big role in production process of electric and electronic components, precision apparatus, optical apparatus, cars and car components, and metal parts (Committee of over viewing novel industrial cleaning technology 1996; JICC 2005). As well as production, corrective maintenance requires cleaning process including repairing process in chemical plants. **Figure 3-1** presents cleaning processes in industrial and consumer activities. Cleaning processes are inevitable for various products and production processes.

For dealing with various types of impurities to be removed from products, many kinds of chemical substances have been utilized as cleansing agents in cleaning processes. **Figure 3-2** shows the chemical substances utilized as cleansing agent for industrial processes. Historically, the first substances for cleansing agent were water and flammable hydrocarbon. After trichloroethylene (TCE) production in Japan had started in 1934, chemical substance utilized as cleansing agent was mostly shifted to chlorinated agents, especially TCE and perchloroethylene (PERC) in 1970. These nonflammable chemicals have high solubility and enables vapor washing, which can clean various parts and products precisely. 1,1,1-Trichloroethane (1,1,1-TCE), which is also highly adaptable chemical, also came into use for industrial cleansing agent in 1961, because of its lower hazard than TCE.

In contrast to the positive history of chlorinated chemicals as cleansing agents, such chemicals caused problems on environmental pollution, and then, the Law Concerning the Evaluation of Chemical Substances and Regulation of their Manufacture and the Water Pollution Control Law was enacted to reduce the use of hazardous material including TCE and PERC. These political movements drove the trends of cleansing agent to 1,1,1-TCE as shown in **Figure 3-3**. On the basis of global impacts of ozone layer depletion, however, 1,1,1-TCE and chlorofluorocarbon-113 (CFC-113) were banned and must phase out the production and use in open-system from 1995. To obtain the agent market which was 200,000 $t \cdot yr^{-1}$ only by 1,1,1-TCE, various cleansing agents had been developed and cleaning sites, having utilized 1,1,1-TCE, CFC-113 substituted hydrocarbon (HC), alcohol, brominated solvent, other chlorinated solvent, aquatic detergent for 1,1,1-TCE. Consequently, the complicated usage of chemical substances as shown in **Figure 3-2** have been created. The total emission in Japan is shown in **Figure 3-4** from 2001 to 2006. The latest results show the emission of chlorinated solvents has the same magnitudes with that of surfactants included in aqueous detergents in industries and consumers (MOEn 2008b).

In such a cleaning process, however, the emissions of substituted substances to the environment and occupational impacts have frequently become a problem (MOEn 2007). As well as TCE and PERC, dichloromethane (DCM) has drawn attention as a cause of both green house effect gas (GHG) and volatile organic compound (VOC) emissions in Japan (MOEn 2007, 2008c). Although the installation of closed-loop washing machines could reduce such emissions in Germany (von Grote 2003), it is not a viable solution for all cleaning sites to install a sufficient number of closed-loop washing machines to maintain the throughputs of products. This is because the throughput of a closed-loop washing machine is generally lower than that of an open-top one and most of the cleaning sites in Japan are small and medium-sized enterprises (SMEs) or family-owned ones having severe restrictions on space and fund for the installation and the investment. Some scenarios using TCE and an aqueous detergent were analyzed by LCA (ECSA 1996), which cannot easily be applied to the risk reduction in SMEs because the adoption of an aqueous process requires big capital investment and large space for waste water treatment.

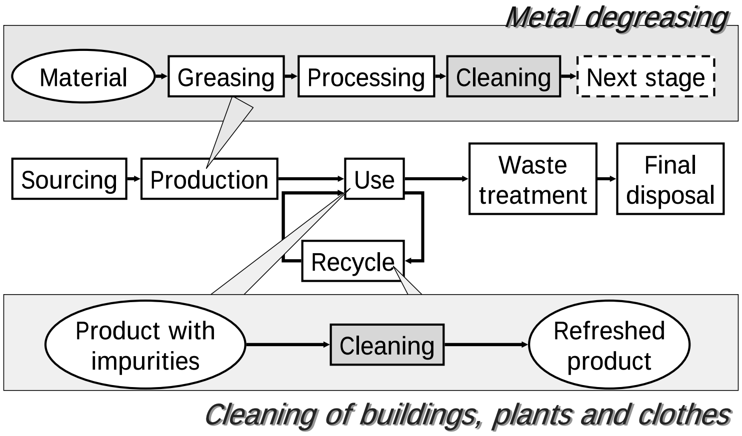


Figure 3-1 Cleaning processes in industrial and consumer activities

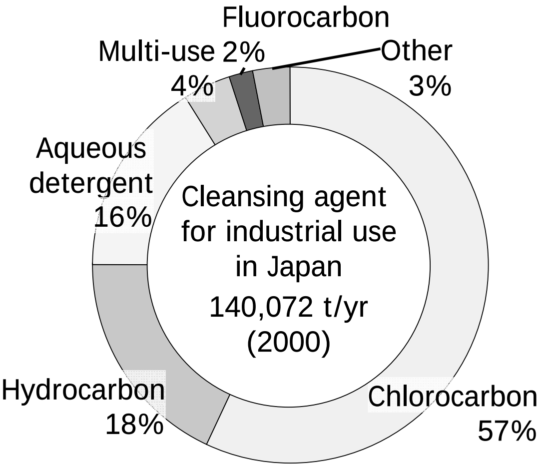


Figure 3-2 Chemical substances utilized as cleansing agent (NEDO 2003)

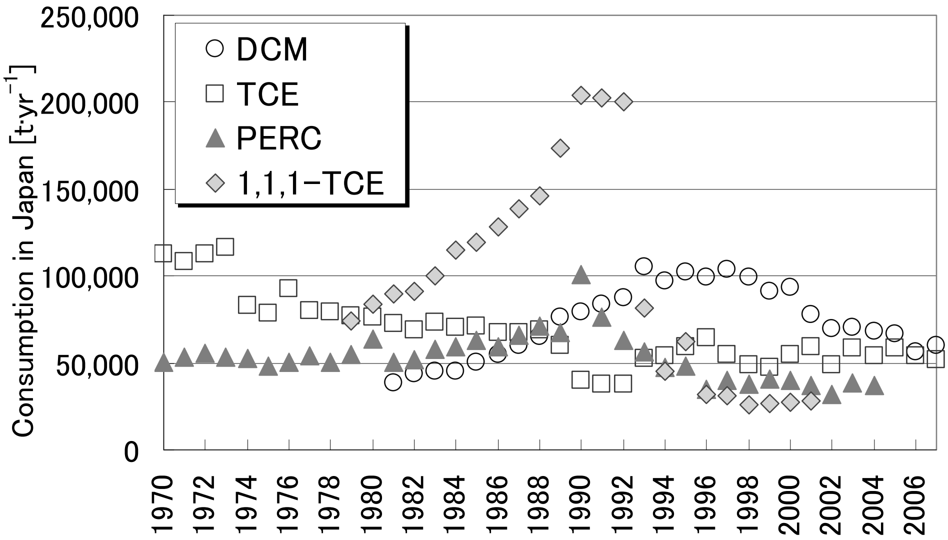


Figure 3-3 Changes in the consumption of chlorinated solvents in Japan, which include all usage of them.

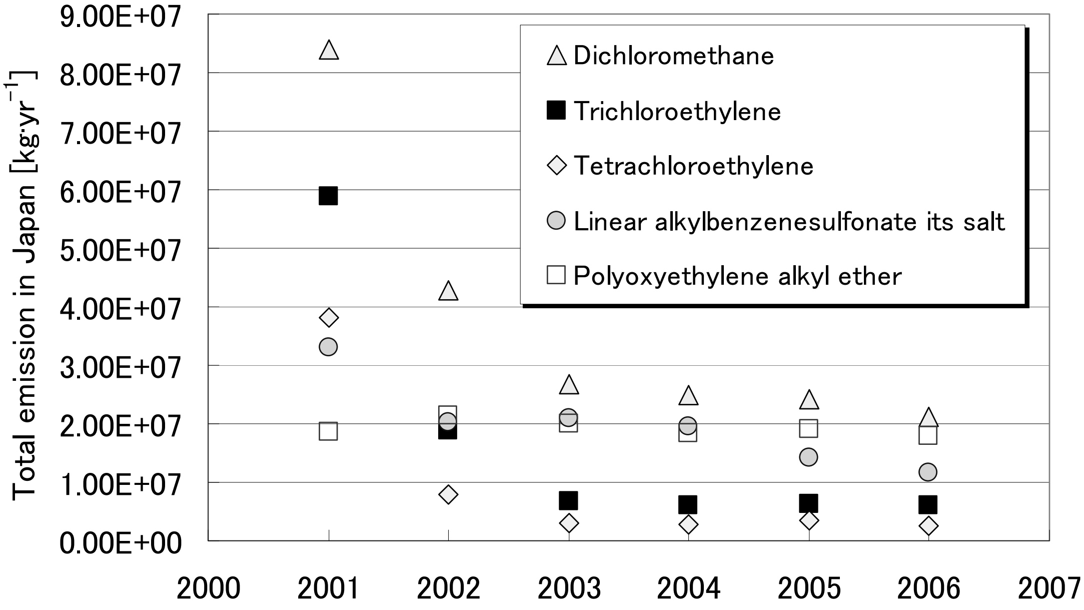


Figure 3-4 Total emission amount in Japan including notified and estimated amount in PRTR investigations.

3.1.2. Overview of Process and Technology

Figure 3-5 schematically shows the cleaning process system including required components. **Table 3-1** characterizes the representatives of existing metal cleaning processes. **Table 3-2** shows process parameters of a cleaning process. Various cleaning processes can be generated by considering these parameters. Additionally, it has been empirically proved that the cleaning performance and the amount of input/output of cleansing agents and waste oil are greatly sensitive to all these parameters.

The cleaning process must have the well balanced components for cleaning requirements. Chemical and physical functions achieved by chemical substances and machines are the main ability of cleaning attributable to the process. Operational conditions support and activate these functions. Various types of objects must be cleaned in processes on size, shape, material, state of surface, cleaning requirement and so on. The objects with fine pores are known as one of the most difficult objects to clean. On the other hand, there are simple objects to clean such as cast-iron pan. The cleaning difficulty is considerably different from object to object, and thus, the cleaning process should be selected on the basis of cleaning difficulty and cleaning requirement. In this regard, however, the qualitative and quantitative requirements for the degree of cleanness are mostly determined by the following processes such as electroplating, mounting, painting, and soldering.

The quality matters are informed as the return of lots from downstream processes. To fit the plant-specific constraints, metal cleaning has been highly-diverse processes in several decades as shown in **Figure 3-6**.

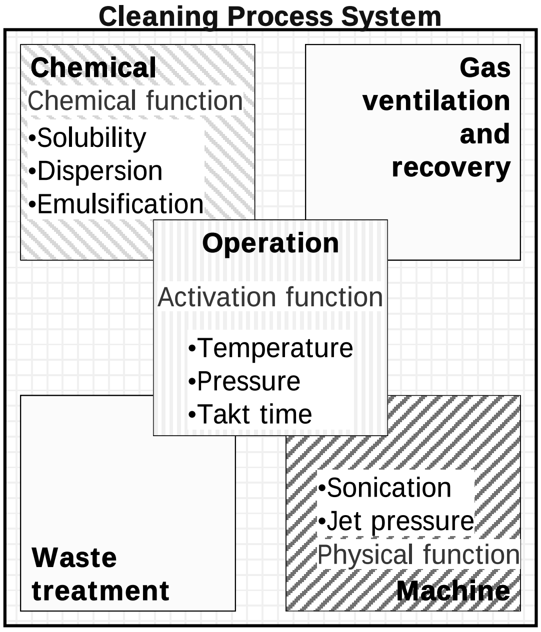


Figure 3-5 Overview of cleaning process system

Table 3-1 Compilation of main features of industrial cleaning processes

	Systems using aqueous cleansing agent	Systems using chlorinated solvent	Systems using non-halogenated solvent
Cleansing agent contents	Surfactant (anionic, cationic, nonionic), Detergent builder (phosphate, borate, etc), Auxiliary agent (stabilizer, fragrances, etc)	Trichloroethylene, Tetrachloroethene, Dichloromethane, Auxiliary agent (stabilizer)	Alkane (n-paraffin, isoparaffin, etc), Alcohol and ether (alkoxypropanol, isopropanol, etc), Auxiliary agent (stabilizer, additive, etc)
Cleaning technique	Cleaning bath, Rinsing bath, Mechanical treatment(ultrasonic wave, spraying, etc), Drying(hot air, etc)	Cleaning bath, Rinsing bath, Vapor degreasing, Mechanical treatment (ultrasonic wave), Drying (hot air, vacuum)	Cleaning baths, Vapor degreasing (limited), Mechanical treatment (ultrasonic wave), Drying (vacuum)
Recycling and waste treatment technique	Bag filtration, Oil-water separation, Sedimentation, Ion exchange, pH control	Bag filtration, Distillation, Activated carbon recovery, High pressure and deep cooling recovery, Oil-water separation, Exhaust gas treatment	Bag filtration, Distillation, Oil-water separation, Exhaust gas treatment

Table 3-2 Example of process parameters of a cleaning process

Continuous parameter	Discrete parameter
➢Temperature of the cooling pipe ➢Height of the freeboard ➢Freeboard ratio ➢Batch number of cleaning a day ➢Design parameters of peripheral devices (airflow of ventilation, recycle ratio)	➢Cleansing agent ➢Open/close machine ➢Installation or not of peripheral devices (recovery and recycle system, local ventilation system, waste treatment system) ➢Cleaning operation method

As well as the plant-specific conditions mentioned above, plant-generic conditions are also taken into account in industries. The strongest constraints of them are laws and regulations imposed on specific industrial-sectors utilizing some targeted chemicals. In Japan, the Industrial Safety and Health Law (ISHL) and the Ordinance on Prevention of Organic Solvent Poisoning (OPOSP) have controlled cleaning processes using organic solvents (MHLW 2004). Waste treatment, especially for waste water, must be installed in all aqueous cleaning process. Gas ventilation system must also be installed and recovery system is recommended. Although the installation of room-air exchange system is obligated, the method and device of ventilation is relegated to on-site engineers, and many sites installed local ventilation systems. There are many types of local ventilation system for open-top washing machine which can classify and divide the actual cleaning processes into 3 groups. **Figure 3-7** shows the three types of local ventilation system installed into open-top washing machines, which have been normally utilized in cleaning processes. The investigations of law-abiding usage of organic solvents are conducted by the measurements of workplace concentration at two times per year. There are regulation rates of local ventilation, which can be interpreted as the minimum rate obligated to local ventilation. With inappropriate local ventilation, the air flow of ventilation has to be increased to achieve the regulation, which can disturb cleansing agents inside of washing machine. If the inlet of ventilation was installed and designed inadequate shape and position, it might result in the increase of workplace concentration as well as agent consumption.

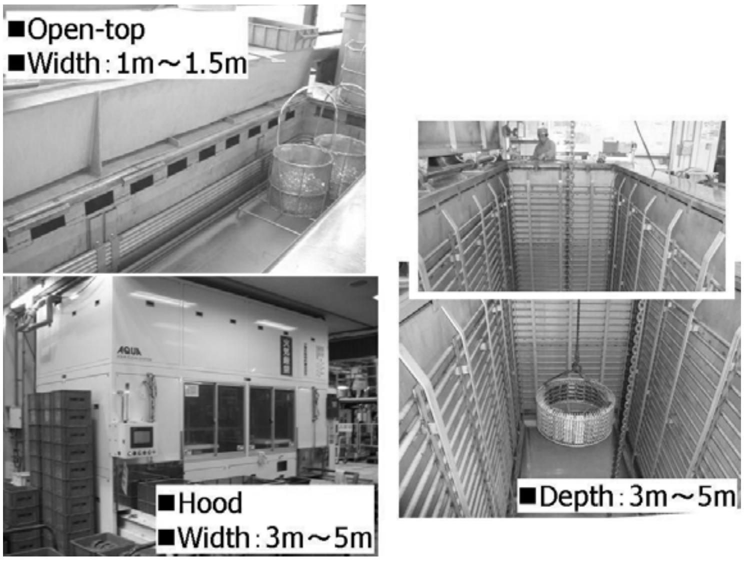
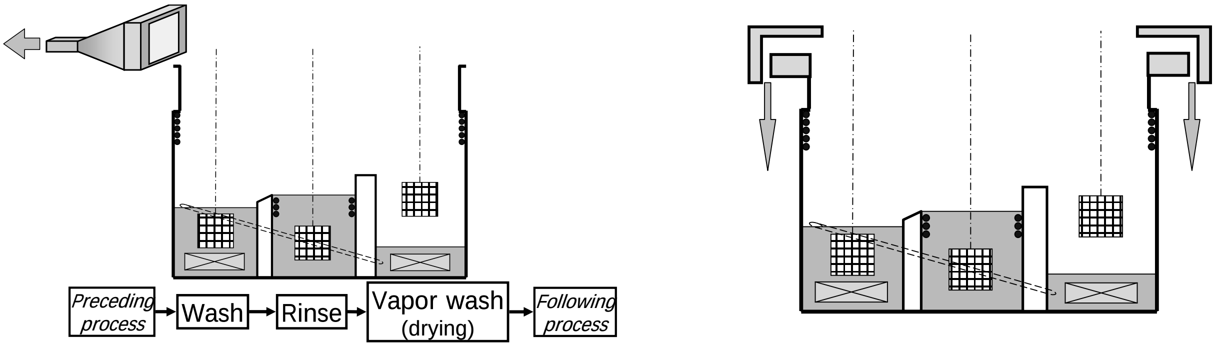
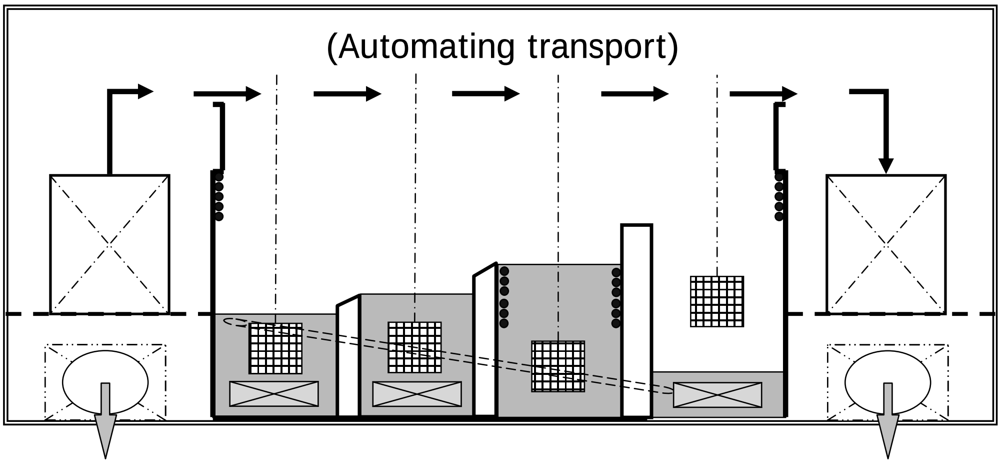


Figure 3-6 Highly-diverse metal cleaning process in industries



(a) Exterior type

(b) Enclosed-exterior type



(c) Enclosed-hood type

Figure 3-7 Open-top washing machine with local ventilation systems

3.1.3. Process Functions and Constraints in a Supply-Chain

Cleaning process is located after or before the main metal manufacturing processes, such as metal cutting or pressing followed by cleaning and plating or heat treatment following cleaning. **Figure 3-8** illustrates a cleaning process with related material life cycles. At a process, the life cycle of product and that of process chemical are intersected each other. With regarding to metal cleaning process, the process chemicals are cleansing agents and the material for utility, and products are metal parts to be cleaned. The features of inputted objects, including metal parts and impurities to be removed, are regarded as one of the constraints, which are from upstream stages in the product life cycle. The requirements from following processes, which are cleaning requirements and throughputs, are also one of the constraints. Process devices and operations have been designed to achieve process functions meeting such process constraints. **Table 2-4** organizes the relationships between constraints and functions with required process components. They can be mainly divided into plant-specific and generic ones, which can be a factor of local risks and global impacts.

Cleaning process is one of the value-added industries shown in **Figure 1-6**. The objective of a cleaning process is strongly depended on the relation with main process. As the post-treatment process located after cutting or pressing process, the cleaning requirements are not always high according to the following processes. In the contrast, the cleaning process as the pre-treatment process before metal-plating or heat treating processes must achieve high cleaning requirements, because the qualities of such metal-surface treatment process are highly sensitive to the conditions of metal surface. Just a small amount of impurities and particles can lead to the failure of surface treatment, and then, the safety risk of final products composed of metal parts. Therefore, a cleaning process has different aspects based on whether it is the pre or post-treatment process of main metal processing.

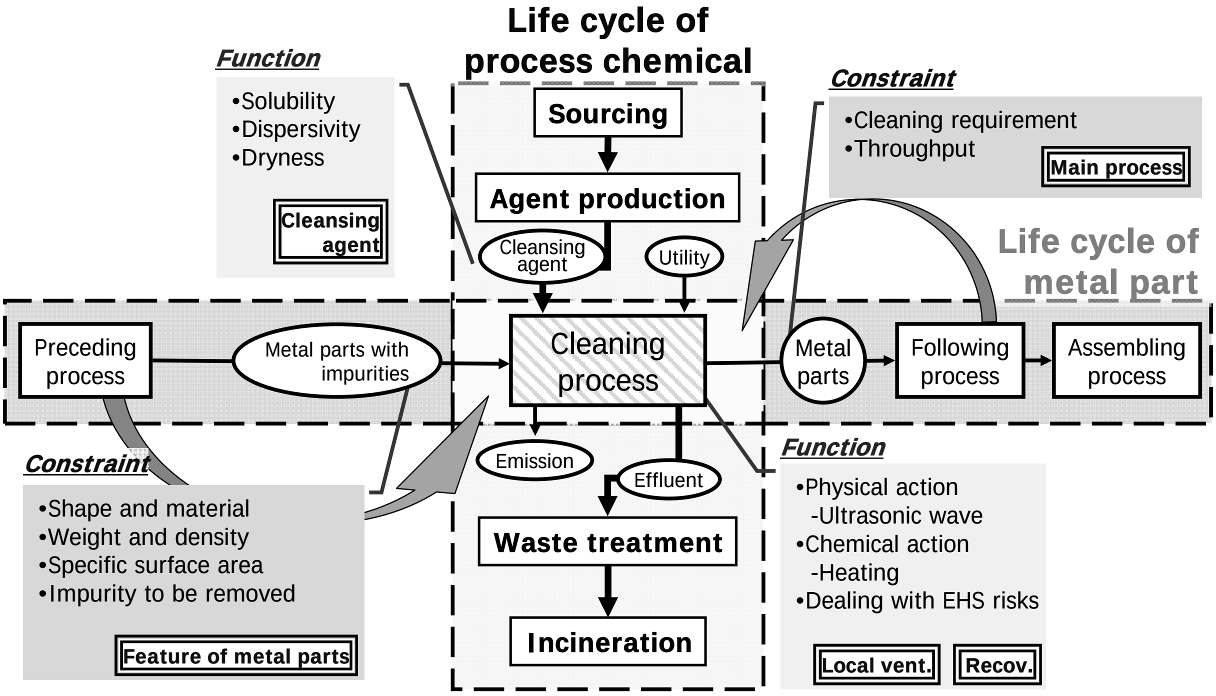


Figure 3-8 Process functions and constraints of a metal cleaning process where the life cycles of cleansing agents (process chemicals) and metal parts (products) are interconnected

Table 3-3 Process constraints with functions required to meet them

Conditions	Process constraint	Process function
Plant-specific conditions	Process phase of cleaning	Cleansing agent, Washing devices(physical and chemical effect)
	Posttreatment of cutting and pressing, pretreatment of surface processing	
	Cleaning requirement	
	Feature of metal part	
	Material, shape	
	Throughput	
General conditions	Air Pollution Control Law	Recovery system, local ventilation system
	VOC discharge regulation	
	Ordinance on Prevention of Organic Solvent Poisoning	

3.1.4. Present Situation of Process Design

In order to get a grasp of the present situation and the problems on the design of metal cleaning process, the interviews to engineers and the investigations on actual plants have been performed including the participation to the projects within Japan Industrial Conference on Cleaning (JICC) as observers or members (NEDO 2003; METI 2005b; MOEn 2007; MOEn 2008b). Five categories of industry related with industrial cleaning were investigated; cleaning site, agent recycling site, manufacturers of cleansing agent, washing machine, and recovery equipment. These companies are mainly related with the cleaning process using chlorinated substances as cleansing agent.

Cleaning site

The forepersons in cleaning sites have deep knowledge of properties related with the process, which are, for example, the impurities of their own products to be cleaned, or the cleaning difficulties originating from specific shapes or materials of products. Additionally, they can evaluate the finish of cleaning appropriately. In the present situation, the forepersons in cleaning site take the initiative to design cleaning process based on experimental trial in manufacturers. At that time, however, there is no assessment on chemical risk or on the environmental effect, because of the lack of skill, knowledge, and information.

Agent recycling site

Agent recycling site is a part of the life cycle of cleansing agent where they mainly distill cleansing agent from the waste fluid outputted from cleaning site. In the present situation, this site has no relationship with cleaning process design. In this regard, however, the forepersons in cleaning processes select the site, to which their waste fluid should be outputted.

Manufacturer: cleansing agent

Manufacturer of cleansing agent is obviously familiar with the quality and the ability of produced agents. After the distribution of cleansing agents, they provide aftercare for troubles in agent usage as one of the activities to enhance customer satisfaction. As the results of it, they can perform some basic troubleshooting on washing machine. Another positive role of them is to perform the cleaning experiment. Some clients visit their plant and perform cleaning experiment. The clients make a decision based on the results of experiment. The selection of cleansing agent is entirely dependent on whether it can meet the requirement of cleaning.

Manufacturer: washing machine

Manufacturer of washing machine is obviously familiar with the structure and the mechanism of own machine. They do maintenance of washing machine regularly, and perform troubleshooting on cleaning. In the present situation, they work like as a consultant for cleaning at annual scheduled maintenances. The cleaning requirements in a cleaning site is subject to change by new products. However, most of the cleaning site can not change the type of used cleansing agent easily, because of the lack of funds. Therefore, they manage to make it possible to clean them. Consequently, process engineers in cleaning sites commission them to do troubleshooting.

Manufacturer: recovery equipment

Manufacturer of recovery equipment is familiar with techniques to reduce the emission volume of cleansing agent by utilizing end-of-pipe equipment. They can select and implement the end-of-pipe equipment. In the present situation, they also work as consultant for reducing the use of cleansing agent. The on-site engineers of cleaning process make discussions on troubles they have with the engineers from recovery equipment manufactures. At that time, some manufactures not only sell their own products, but also play a role as advisers for the chemical discharge control.

3.1.5. Identified Aspects of Problem and Requirements of Solution

Table 3-4 organizes the identified aspects of problem on process design and evaluation in metal cleaning. In order to implement risk-based decision making into practice, a foreperson in cleaning site is proposed as the person who should take the initiative to design a cleaning process, because he knows what is needed for the cleaning closely and can make any decision on the site of the cleaning. Considering the present situation, if there is any trouble which is not happened before, a foreperson in cleaning site cannot make an effective change in the setting of washing machine without the consultation by manufacturers. Even if a trouble with the experience in the past, the empirical knowledge cumulated in cleaning site is merely qualitative one. The example of accumulated empirical knowledge of cleaning site is organized in **Table 3-5**. This knowledge is what is happen by a change of a parameter. On the other hand, the engineers of such related companies can be referred to as the experts of troubleshooting and improvement of industrial cleaning process. The empirical knowledge of each enterprise can be included in the troubleshooting. They have cumulated the experiences on troubleshooting. When a new trouble occurs, however, they have to repeatedly deal with trial and error.

Table 3-4 Identified aspects of problem
on process design and evaluation in metal cleaning

Knowledge on process design and evaluation	·Risk due to the use/emission of cleansing agent ·Persistent avoidance of halogenated chemical ·Application of PRTR registration ·Measurement and standard value on OPOSP ·Management on economic aspects ·No quantitative empirical action to non-monetary issues ·Heuristics on process improvement regarding quality ·Distributed knowledge among related industries ·Uncertainties on open-system process ·No dedicated process model ·Uncertainties on open-system process ·Hazard management ·Trade-off relationship among local risk, global impact, and feasibility ·Excessive weight on results of PRTR investigation ·Constraints from other processes in supply-chain
Business activity and software information system model	·On-site engineers at SMEs in value-added industry ·Lack of knowledge and skill of scientific methods ·Risk reduction with quality maintenance ·Requirement of cost even or reduction ·No business activity model implementing scientific method ·Requirement of software system enabling the execution of process design with the smallest activities by decision-makers ·Development of applicable knowledge ·Business activity modeling ·Software system activating knowledge highly user-friendly

Table 3-5 Example of accumulated empirical knowledge in cleaning site

target parameter	change	result
Ventilation rate	up	Decreasing the concentration of working place
Heater temperature	up	Increasing the volume of vaporized cleansing agent
Heater temperature	up	Increasing the amount of heat-decomposed cleansing agent
Shield on the top	install	Decreasing the emission volume of cleansing agent
Free board height	up	Decreasing the emission volume of cleansing agent
Temperature of cooling water	down	Increasing the reflux volume of cleansing agent
Moving rate of objects	down	Decreasing the emission volume of cleansing agent
Moving rate of objects	down	Extending total takt time

The design of metal cleaning process has been strongly depended on the heuristics of the experts in industries. The objective functions were mostly based on the profit from processes. At this present and historical cases, however, the processes were forced to change chemical substances based on non-monetary issues. Without scientific assessment of risk associated with metal cleaning, the process change may be continued. When we design a production process that uses chemicals, possible risk involved in the operation of the process plant should be identified and reduced comprehensively through decision making. For metal cleaning process design, a method of assessing local risk and global impact should be developed and implemented into business activities of the on-site engineers in metal cleaning sites.

3.2. Investigation on Actual Process

This research needs lots of actual information on metal cleaning processes. The investigation on actual processes was conducted for 33 different processes. At the same time, several interviews were conducted on many engineers in industries related with metal cleaning. Through these activities, the actual situations and conditions on site were clarified.

The objectives of this investigation were to scrutinize plant-specific conditions. The ways of collection are the investigations on site, interviews, and questionnaires for on-site engineers by datasheets shown in **Figure C-1** and **Figure C-2**. The datasheets enable the collection of information in the same form for all sites. It can reveal which information is available on site. The important parts of the investigation results are organized in **Tables C-1 – C-4**. The set of washing machine and local ventilation system can refer to **Figure 3-7**. The investigated processes have a wide range of variation of main processes such as cutting, pressing, plating and heat-treatment processes. The utilized chemicals as cleansing agents in the processes are chlorinated solvents, which are DCM and TCE, and hydrocarbon (HC). Both chlorinated solvents have widely been used because of their inexpensiveness, high ability as a cleansing agent and non-flammability, while a significant amount of emission has become an issue in Japan reported in the latest PRTR legislation result (MOEn 2008a). HC agent has been regarded as the substitution materials for chlorinated one.

For process modeling of metal cleaning process, the lack of understandings on the physical phenomena in cleaning machine is one of the major weak points. The investigation on actual processes in this research can execute the measurements of unknown physical parameters in cleaning sites such as concentrations of agent, ambient airflow rate, and direction. These measurements are the foundational knowledge for process modeling in this research.

3.3. Practical Method of Assessing Local Risk and Global Impact for Risk-Based Decision Making

3.3.1. Introduction

When we design a production process that uses chemicals, possible risks involved in the operation of the process plant should be identified and reduced comprehensively through decision making. Adverse effects originated in the use of chemicals can be mainly divided into the two types configurations; risks during use and after emission. As the further divided risks after emission, there are local EHS risks and regional/global impacts. **Figure 3-9** shows the dominant adverse effects originated in an industrial process: local risks and global or regional impacts. In these adverse effects, safety issues might be included in both the risks during use and after emission, the factors of which are the chemical substances in apparatuses and the residual ones in local microenvironment. Theoretically, these adverse effects must be happened and caused in all processes utilizing chemicals as both raw materials and utilities. An appropriate risk-based decision-making should take into account them through overall life cycles of all related products. A method supporting such decision making can be represented as life cycle risk assessment (LC-RA), by which local risks and regional/global impacts can be addressed in suitable ways. Any method cannot achieve the requirements for LC-RA alone, because the aspects of risk indices to be evaluated are totally different.

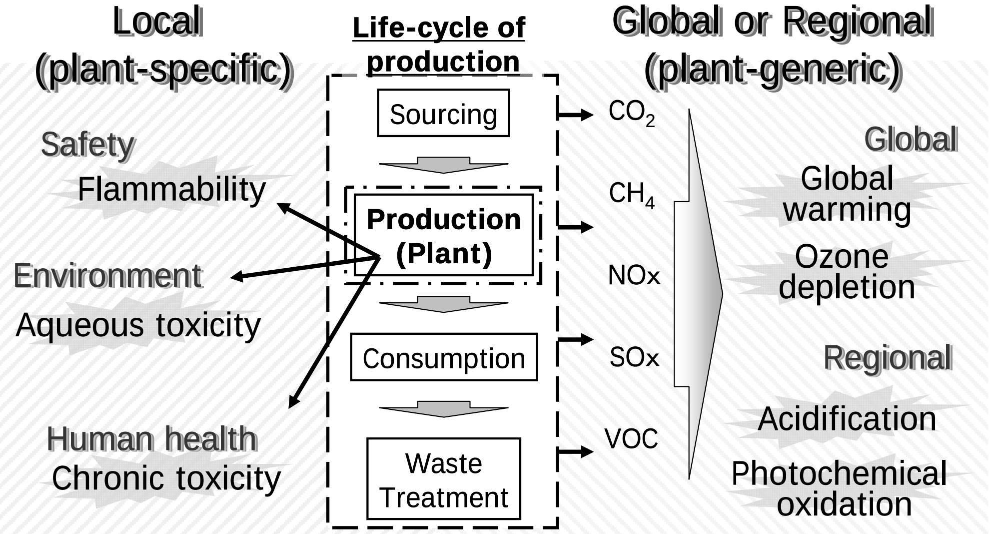


Figure 3-9 Dominant adverse effects originated in an industrial process: local risks and global or regional impacts

The conversion of LC-RA into tangible forms needs several assessment methodologies, which have been developed, to be effectively selected and integrated into a risk-based decision making. Methodologies based on RA are used to qualitatively or quantitatively evaluate the implicit risks involved in the use of chemicals or exposure to them in local area such as a plant or process (Kolluru et al. 1996). In contrast, LCA is a tool for evaluating the potential impacts of the emission of chemicals from the life cycle of a product or materials related to the process (ISO 1997). These methodologies have been applied for the comparison of technological alternatives or for the improvement of the process or operation. There have been several studies on the integration of RA and LCA. The relationships between ERA and LCIA (ISO 2000a) have been discussed in the OMNIITOX project (Molander et al. 2004). The spatial aspects of environmental impacts have been incorporated into LCIA methodologies by providing regional impact categories (Itsubo and Inaba 2003; Haes et al. 2002) and a case study on laundry detergents has been performed (Pant et al. 2004). Although this approach enables us to evaluate ecotoxic impacts by ERA, other local risk categories, such as the health of workers and neighbors and fire/explosion safety, are still difficult to assess. This is because a dynamic exposure such as the direct and accidental inhalation to a chemical, that is impossible to treat in an ordinary LCIA, should be considered in the rigorous assessments of health or safety risks. Additionally, plant-specific conditions, for example, the number of workers, the working schedule, the ambient surroundings of the site, and the emission volume in the workplace with temporal aspects, can be considered in more detail in RA than in LCA. These conditions are considerably sensitive to local risks, which are the major concerns for actual decision making by on-site engineers.

Additionally, several research groups, such as the working-group on indoor exposure models within the task force on toxic impacts under the LCIA programme of the UNEP/SETAC Life Cycle Initiative, have started to integrate indoor exposure models into LCIA (Hellweg 2005; Jolliet 2005). Although several models have been discussed and proposed, their general practicability is not assured so far.

For decision making to reduce chemical risks involved in the processes, alternative technologies should be assessed on the basis of the major concerns. Many SMEs in Japan are located in residential areas, and thus, local impacts, such as occupational and neighborhood risks, as well as global impacts should be considered. Because local risks considerably depend on the individual conditions of cleaning sites, appropriate assessments should be conducted by each enterprise to distinguish alternative technologies and decide effective and viable processes and operations.

This section presents a practical method of assessing local risks and global impacts for a risk-based decision making. The proposed method effectively integrates several existing assessment methodologies in a complementary style. Especially, LCA and RA are targeted as the methodologies to be integrated. In this regard, however, RA employs the evaluation of local EHS risks, which occurred in microenvironments such as workplaces and neighborhoods around processes. Therefore, this section limits targeted RA to plant-specific one, which assesses local EHS risks on plant-specific conditions such as ambient surroundings, workplace conditions, and operations.

3.3.2. Association of Knowledge on Evaluation

The objectives of LCA and RA are originally different on the targets they mainly focus on. This section discusses the different and common points of them. Evaluation procedures of LCA and plant-specific RA are organized in **Figure 3-10** based on general ones (ISO 1997, 1998, 2000a, 2000b; Kolluru et al. 1996). The solid arrows represent the procedures, and the dot-line arrows are data or model requirements in each activity represented by boxes. The main phases of both methodologies are objectives settings, collection of technical data, evaluation of effect and interpretation. Although their structures are quite similar, the meanings and targets of evaluation results are greatly-differing because of the differences of the properties of data requirement and its handling.

RA is a methodology revealing and quantifying the risk caused by a substance. Practitioners can flexibly define targets and exposure scenarios along with their assessment purposes, for example, if they want to clarify the occupational risk due to the use of a substance, exposed being should be set as workers operating devices with the substance, and exposure scenario should be based on the working schedule. In addition to the flexible definition of evaluation settings, at effect analysis, the result has a physical meaning as an absolute value, because of easy calculation using hazardous properties, which enables a decision-maker to judge with a physical reality whether the risk can be acceptable. Moreover, the range of required technical data, which is the process data of their own processes, is narrow enough for on-site engineers to collect easily. There are plenty of evaluation styles in RA, which are derived from various assessment purposes and individual conditions.

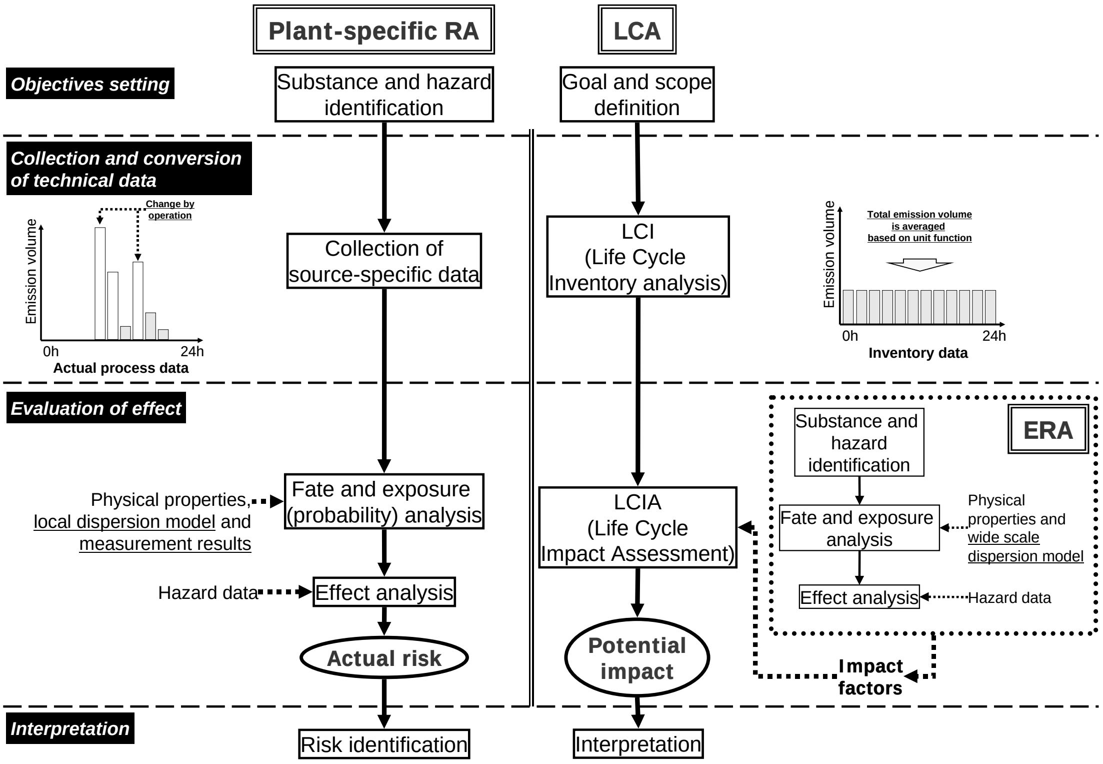


Figure 3-10 Evaluation phases of plant-specific risk and life cycle impact assessment with data requirements

LCA has a framework standardized in ISO14040, which somewhat obligates practitioners to go through the procedures. In the framework, functional unit and system boundary must be defined with logical fitting to the objective of assessment. Based on the defined settings, the life cycle fulfilling the defined functional unit and the emissions to be accumulated should be specified. In LCI analysis, practitioners might conduct allocation of process data to enable the summation of inventoried indices in all life cycle stages. For the LCIA, impact factors based on unit emission amount should be maintained for each emission. These activities enables the quantification of the environmental impacts through life cycles. In this regard, however, because the release conditions of each emission are spatially and temporally different and there is usually time lag between releases and impacts in a strict sense, the evaluation results are not always physically meaningful as absolute values but potential values. A decision-maker should use the results as relative criteria.

According to the procedures shown in **Figure 3-10**, there are common or similar information required for each assessment. For the complementary integration of LCA and plant-specific RA, data and information should be shared during a phase in both assessments each other as well as possible. Especially in objective settings and interpretation, the activities stay in close contact to share information for the avoidance of ineffective and inadequate settings of redundant items and interpretation on a narrow field of vision. The followings are the detail descriptions of each phase with regard to the required information.

An alternative process will be decided with achieving installation feasibility as well as with meeting the reduction target and other constraints. Several aspects are taken into account as key installation feasibilities in decision making; effect on process function, economic feasibility, installation location and construction conditions. In this time, the cost requirements can be regarded as the investments to reduce risk. It means low cost is not always a strong decision factor. If necessary, additional costs should be accepted for a sufficient reduction in risks. In such cases, generated feedback information will become a new constraint for further improvements of process or budget. With regard to the installation location and construction conditions, the timing of stopping the running process to replace with alternative one might become a critical items for on-site engineers to be taken into account in decision making.

3.3.3. Case Study: Running Process Assessment

This subsection presents a case study of assessing actual metal cleaning processes by LCA and plant-specific RA. This case study aimed to analyze the difference of local risks and global impacts among processes under individual conditions and to reveal the practicability of data collection by on-site engineers. Required data were collected through several investigations on sites. LCA and plant-specific RA were executed on the collected actual process data.

Method

Plant-specific Risk Assessment

According to the existing health risk assessments of DCM and TCE on the general exposure in Japan (Nakanishi et al 2005; Kajiwara et al 2008), the initial exposure route of them is inhalational exposure. This study scopes the inhalational exposure of the two chlorinated carbons to workers in workplace and neighbors in neighborhoods around cleaning processes. Several indicators have been proposed as the indicators for health risks and the selection should be carefully performed on the sake of assessments (Kikuchi and Hirao 2008a). In this regard, however, the difference of indicators are mainly caused by the effect analyses in RA. The exposure analyses are almost same in several indicators. Based on this fact, the predicted daily intake (PDI) [$mg \cdot kg^{-1} \cdot day^{-1}$] and the predicted total exposure amount (PDI_{total}) [$mg \cdot day^{-1}$] are evaluated as the local risks. Therefore, the indicators of plant-specific RA are set as workers' health risks indicated by PDI_{worker} and PDI^{total}_{worker}, and neighbors' health risks indicated by PDI_{neig} and PDI^{total}_{neig}.

$$PDI = \sum \left(C_i \cdot V_{inh} \cdot \frac{\Delta t_{exposure,i}}{hr_{day}} \right) \qquad (3\text{-}1)$$

$$PDI^{total} = N_{exposed} \cdot BW_{ave} \cdot PDI \qquad (3\text{-}2)$$

where Ci : concentration of dichloromethane which the human is exposed to ([$mg{\cdot}m^{-3}$]), V_{inh}: inhalation volume per person a day (20 ($m^3{\cdot}person^{-1}$)$\cdot day^{-1}$), $\Delta t_{exposure,i}$: exposure time duration at Ci [h], hr_{day}: hours per day (24 h), $N_{exposed}$: the number of exposed human ([person]), and BW_{ave}: average body weight (65 $kg{\cdot}person^{-1}$). PDI was estimated by exposure analysis with eq. (4.1). Workers and neighbors who were exposed to DCM and TCE at various daily temporal concentrations are defined. Workers are exposed to solvents at the workplace concentration for 8 $h{\cdot}day^{-1}$ and at the background concentration in Tokyo for 16 $h{\cdot}day^{-1}$.Neighbors are exposed to solvents at the concentration around the cleaning sites for 24 h.

The C_{work} and the number of exposed workers (N_{work}) were obtained by the investigations on 31 processes as actual data on sites. In this time, the investigations were based on the different situations; the average concentration with the total number of workers and the maximum concentration with the number of workers operating cleaning machine. As well as the data on workers' exposure, the data required on neighbors' exposure were collected. The C_{neig} was estimated by the emission rate from sites and a dispersion model under the local meteorological conditions (Meteorological Office 2003), Ministry of Economy, Trade and Industry-Low rise Industrial Source dispersion (METI-LIS) model (METI 2005a). The defined settings of dispersion model are the range of calculation, calculated height from ground level, and the value condition, which are 1 square kilo-meter around a cleaning site, 1.6 meter from ground level, and average and maximum concentrations, respectively. The numbers of exposed neighbors (N_{neig}) are set corresponding with the actual population densities of the local public area where each site is located.

Life Cycle Assessment

LCA aimed to quantify the environmental impacts associated with a metal cleaning process. Although there may be various functional units for cleaning (Finkbeiner 1997; Ruhland 2000), the metal cleaning function can be based on the quantity of production. “Daily operation of cleaning” and “Cleaning of unit amount of metal parts” were adopted as functional units.

The system boundary includes the life cycle of cleansing agents and the materials for utilities inputted in all life cycle stages of cleansing agents. The typical life cycle of cleansing agent is shown in **Figure 3-11**. The reference flows inventoried in this paper are organized in **Tables C-1 – C-4**. The inventory analysis was based on the process foreground and background data obtained by the investigations and released databases (JLCA 2008; JEMAI 2005), respectively. In particular, based on process foreground data organized in **Tables C-1 – C-4**, LCI includes the productions of all inputted materials in cleaning and waste treatment processes and oil sourcing and refinery processes for required materials. While agent production processes are included in the system boundary from oil productions, the productions of the installed devices, such as washing machines and ventilation systems, are not investigated. The materials inputted to the cleaning site are cleansing agents and metal parts with cutting oil. Outputted materials are waste fluid, which is transferred to a waste treatment site, and cleaned metal parts, which are transferred outside the system boundary. The environmental loads at the cleaning site are cleansing agents and emissions originated in the combustions of fuels. At the waste treatment site, pure cleansing agent is distilled from waste fluid and outputted as a fresh one. The utilities required for recycling agents are kerosene and electricity, which are inventoried in LCI. Soda ash for the dehydration of agent is also surveyed. The environmental loads at the waste treatment site are the loss of agents and oxides produced by the combustion of kerosene. The residue of waste fluid is incinerated and the emission is included. In the system boundary of cases installing recovery system by activated carbon, the production and desorption of activated carbons are included.

The inventoried emissions are CO_2, CH_4, N_2O, SO_x, NO_x, HC, which is the representation in databases including n-C_{10}, n-C_{11} and n-C_{12}, and cleansing agents, or DCM and TCE. LIME 2nd version was applied as the impact assessment method in LCIA and the indicator was defined as DALY originated in global warming, air pollution in urban area, photochemical oxidant creation and human toxic chemical. The indicators of LCA are set as human health indicated by DALY on the basis of unit amount of metal parts ($\text{LC-DALY}_{\text{kg}}$ [$\text{DALY}\cdot\text{kg}^{-1}$]) and that on daily operation ($\text{LC-DALY}_{\text{day}}$ [$\text{DALY}\cdot\text{day}^{-1}$]).

Because the process inventory of producing hydrocarbon for cleansing agent could not be available in existing databases, it was estimated from available process information and ASPEN Plus®, a general chemical process simulator (Aspen Tech 2004).A major hydrocarbon utilized as cleansing agent can be obtained by precisely separating from kerosene using molecule sieve method (JPI 1998, 2001; McPhee 2000). In this case study, based on these facts, the process utility and raw material consumption for unit production were estimated by RadFrac rigorous column simulator in ASPEN Plus.

The environmental loads are inventoried using the following categories: agent production, cleaning, waste treatment, incineration and recycled agent. The recycled agent can be regarded as a fresh agent, and then, the same amount of it is reduced in the use of cleansing agent. The life cycle of products to be cleaned are involved in the life cycle of the cleansing agent in the cleaning process. In the cleaning process, there are two types of cleansing agent emission: emission released into the air after filling the workplace and emission released directly into the air through local ventilation. The former emission has both indoor and outdoor effects, and the latter has an outdoor effect.

Results

Figure 3-12 shows LC-DALY$_{kg}$, PDI$_{worker}$ and PDI$_{neig}$. **Figure 3-13** shows LC-DALY$_{day}$, PI_{worker}^{total} and PI_{neig}^{total}. According to the LCA results of these figures, the cleaning process has the highest contributions to LC-DALYs, which ranged 72 to 98%. These figures demonstrated the difference in the profiles of two LCA results. This is because the throughputs of each process have a connection with the agent consumption. Despite the big differences in the process characteristics, there are only fine differences in the emission amounts of cleansing agents and the LC-DALY$_{kg}$ of all processes, which are corresponding to the existing results (Kikuchi and Hirao 2008b).

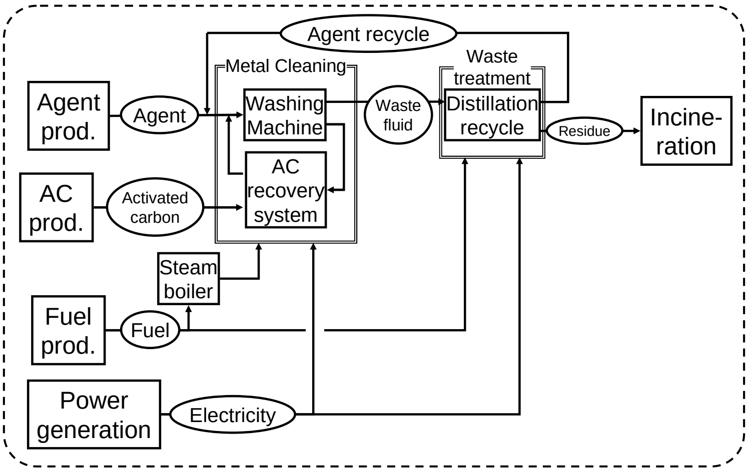


Figure 3-11 Typical life cycle of cleansing agent

With regard to workplace concentration, the standard control concentrations of DCM and TCE are regulated by ISHL, being 50 and 25 ppm, respectively. On these concentrations, the $\mathrm{PDI}_{\mathrm{worker}}$s of DCM and TCE are 1.78E+01 $\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$ and 1.40 E+01$\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$, respectively. Comparing these values and **Figure 3-12**, the average concentrations of most of cases are near to the regulation values. In this regard, however, the maximum concentrations by cleaning exceed the regulation values in some cases. The $\mathrm{PDI}_{\mathrm{neig}}$s in **Figure 3-12** are originated in the total agent emission, which is the main cause of $\mathrm{LC\text{-}DALY}_{\mathrm{day}}$s. This is why there is a similar profile between these values. According to the average exposure amounts of DCM and TCE, being 8.74E-04 $\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$ and 1.75E-04 $\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$, calculated by their average concentrations in Japan (Nakanishi et al 2005; Kajiwara et al 2008), the $\mathrm{PDI}_{\mathrm{neig}}$s around cleaning processes are not negligible to evaluate for process analysis. In this regard, however, the $\mathrm{PDI}_{\mathrm{neig}}$s in **Figure 3-12** are less than the 9.21E+01 $\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$ and 2.18E+01 $\mathrm{mg \cdot kg^{-1} \cdot day^{-1}}$ for DCM and TCE, respectively, which are obtained by the calculation based on the chronic thresholds for both chemicals. The margins of exposure (MOEs) for initial RA (Nakanishi et al 2005; Kajiwara et al 2008; US-EPA 2008b) of each case were figured out. They were more than the uncertainty factors of utilized thresholds, being 100 for both chemicals (Nakanishi et al 2005; Kajiwara et al 2008). This means that there are no significant risks originated in the emitted cleansing agents for neighbors.

The $\mathrm{PDI}_{\mathrm{worker}}^{\mathrm{total}}$s shown in **Figure 3-13** have different profiles to those in Figure 4, because of the evaluation with $\mathrm{N}_{\mathrm{worker}}$s, one of the plant-specific conditions. This is the same situation as the $\mathrm{PDI}_{\mathrm{neig}}^{\mathrm{total}}$s which are based on the population densities of each province, each process is located in. Although the $\mathrm{PDI}_{\mathrm{neig}}$s are much smaller than $\mathrm{PDI}_{\mathrm{worker}}$s in **Figure 3-12**, the $\mathrm{PDI}_{\mathrm{neig}}^{\mathrm{total}}$s and $\mathrm{PDI}_{\mathrm{worker}}^{\mathrm{total}}$s have same magnitudes in **Figure 3-13**, because $\mathrm{N}_{\mathrm{neig}}$s are higher than $\mathrm{N}_{\mathrm{worker}}$s in each process. This is why $\mathrm{PDI}_{\mathrm{neig}}^{\mathrm{total}}$s are considerably depended on the location area.

Case 32 is the process utilizing HC solvents in washing machine. Although HC is regarded as the alternatives considerably reducing environmental impacts in cleaning process, the result demonstrate that some processes utilizing DCM or TCE can keep the impacts as low as that those in HC process.

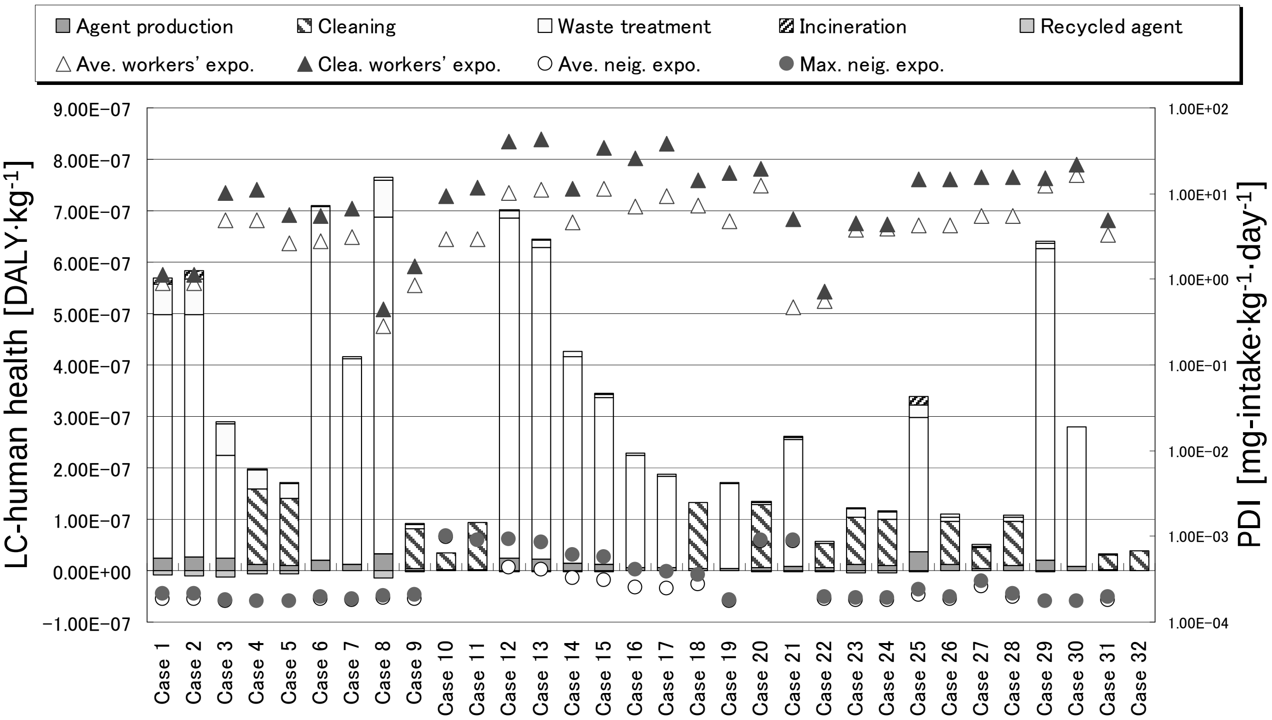


Figure 3-12 LC-human health indicated by DALY and the daily intake amounts of workers and neighbors on the basis of the unit amount of metal parts and daily operation, respectively

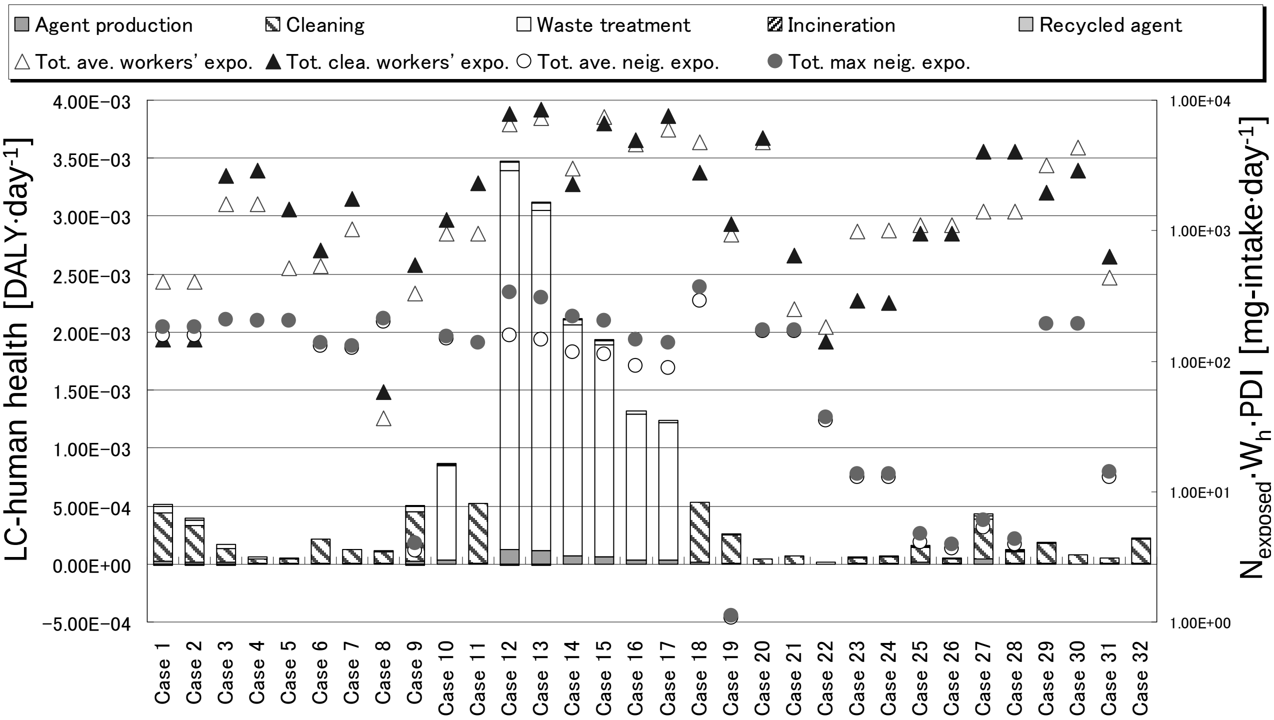


Figure 3-13 LC-human health by DALY and the total intake amounts of workers and neighbors on the basis of daily operation

Local risks and global impacts attributable to metal cleaning processes were evaluated on workers' and neighbors' health risks and global human health impacts. The results of local health risks indicated by PDI revealed such risks are higher than those originated in the national average concentration. The site-dependency of total exposure amounts were dominantly demonstrated in the evaluation results, which were calculated by utilizing the actual number of exposed workers and populations. Although the relationships were addressed among PDIs, total exposure amounts in microenvironments, and the agent emission as a whole and each unit amount of product, they were not simple, because several plant-specific conditions are ones of the dominant factors of each evaluation results. In order to clarify the relationships of process conditions, a careful interpretation of evaluation results was conducted and revealed local risks have different features from global impacts.

3.3.4. Case Study: Alternative Candidates Assessment

Assessments of alternative candidate processes are described in this subsection. For the alternatives evaluations, required process data must be estimated by available resources such as literatures, process models, and experiments. Additionally, the evaluation indicators of local risks and global impacts should be carefully selected to activate the comparative risk-based decision making.

Method

Scenario Settings

This case study is based on an actual degreasing plant where the running process utilizes DCM as a cleansing agent with an open-top washing machine as shown in **Figure 3-7**. The site is located in a residential area in Tokyo, Japan. In this case study, alternative scenarios regarding the running process are defined and compared in terms of the local and global impacts of using dichloromethane.

The running process of the targeted site is defined as the base case. The loss of DCM from the washing machine is assumed to be the dominant cause of the risks in this case study. Several alternative technologies can be used for risk reduction. In this paper, alternative scenarios regarding a local ventilation system and an adsorption system are considered. A local ventilation system used in metal degreasing is the device located around the emission source of the washing machine, which is the opening of the machine. In addition to this local ventilation system, other ventilation devices for air exchange are installed in sites. The detailed descriptions of alternative scenarios are shown below and organized in **Table C-4**.

- Base case (represented as Case 33 in **Table C-4**)

Exterior-type ventilation is utilized as local ventilation. The exhaust opening of this ventilation system is vertically aligned with respect to the opening of the washing machine, as shown in **Figure 3-7**-(a).

- Case 1: decreasing the local ventilation rate (represented as Case 34 in **Table C-4**)

An inadequate flow rate causes a disturbance in the vapor zone in washing machines. This disturbance makes the layer of the vaporized agent unstable and splatters the agent, and then, the agent is drawn into the ventilation system at more than the required amount for keeping the workplace safe. To determine the appropriate flow rate, the flow rate is decreased in case 1.

- Case 2: increasing the local ventilation rate (represented as Case 35 in **Table C-4**)

In contrast to case 1, the local ventilation rate is increased in case 2. This may lead to an increase of disturbance in a washing machine.

- Case 3: changing the type of local ventilation system (represented as Case 36 in **Table C-4**)

In case 3, an enclosed-hood type ventilation system is substituted for the exterior type one used in the base case. The enclosed-hood ventilation system, shown in **Figure 3-7**-(c), is generally regarded that contributes to the reduction in the forced expulsion of cleansing agents from the opening of a washing machine.

- Case 4: installing an adsorption system with activated carbon
  (represented as Case 37 in **Table C-4**)

An adsorption system with activated carbon is installed at the end-of-pipe of a local ventilation system, which is a commonly used system for recovering organic solvents. DCM adsorbs on it, and then it can easily be desorbed by heat and recycled as a fresh cleansing agent.

Plant-specific Risk Assessment

The physical and hazardous properties of dichloromethane can be obtained from the chemical database (CIS 1996) and the literature (Nakanishi and Inoue 2005) (see **Tables E-1**). All risks caused by the properties of DCM should be taken into account ideally. Among the several hazardous properties of DCM, chronic toxicity was selected for the evaluation of occupational and neighborhood risks within an area of 1km^2 around the cleaning site. Inhalational exposure can be assumed as the dominant route of the local risks. There has been few cases of fire and explosion due to the use of DCM. DCM was reported as a possibly-carcinogenic substance, but not a carcinogenic substance to humans by some organizations including Japan Society for Occupational Health (JSOH 2006). Disability adjusted life years (DALY) (WHO 2007) can be used to quantify the chronic risks in occupational and neighborhood areas. DALY is a useful indicator that considers various adverse effects of chemicals on human health. Some LCIA methods utilize it to determine the overall human health impacts by calculating and accumulating the DALYs resulted from different environmental impacts (Haes 2002). Therefore, DALY was selected to discuss the relationship between local and global impacts using the same indicator.

Several discussions exist as to how DALY should be estimated in order to meet the needs of decision making. This paper applied the equation (5.3) from a literature (Pennington 2002) to calculate the DALY of local risks, which was adopted in the life-cycle impact assessment method based on endpoint modeling (LIME) (Itsubo and Inaba 2003, 2005).

$$\mathrm{DALY}_{\mathrm{local\,risks}} = \mathrm{PDI}_{\mathrm{dichlo,inh}} \cdot \left(\beta_{\mathrm{ED10h,\,dichlo}} \cdot \frac{1}{\mathrm{BW}} \cdot \frac{1}{\mathrm{LT}} \cdot \frac{1}{\mathrm{N}_{365}} \right) \cdot \mathrm{DALY}_{\mathrm{chronic}} \cdot \mathrm{N}_{\mathrm{exposure}} \tag{3-3}$$

where $\mathrm{PDI}_{\mathrm{dichlo,inh}}$: predicted daily intake of dichloromethane by inhalation per person ([(mg-intake・person^{-1})・day^{-1}]),$\beta_{\mathrm{ED10h,dichlo}}$: slope factor of dichloromethane ([risk・((mg・kg^{-1})・day^{-1})$^{-1}$]), BW: body weight per person (65 kg・person^{-1}, LT: lifetime of human (70 years), N_{365}: number of days per year (365 days・year^{-1}), $\mathrm{DALY}_{\mathrm{chronic}}$: DALYs per chronic incidence and person ([DALYs・incidence^{-1}]), and $\mathrm{N}_{\mathrm{exposure}}$: number of exposed people ([persons]).

The measured concentration for achieving ISHL can be utilized for the evaluation of occupational risks. The background concentration in Tokyo, Japan 20 $\mu g \cdot m^{-3}$ as Kanto region was obtained from the literature (Nakanishi and Inoue 2005). For evaluating the neighborhood risks, the concentration in the surrounding area is required. Thus, it was calculated using the METI-LIS program version 2.03 (METI 2005a), which employs an atmospheric diffusion model. The METI-LIS program can calculate the concentration of dichloromethane around the breathing zone of neighbors, about 1.5 m above the ground. For this calculation, the rate of DCM emission from the plant chimney, the height of the chimney and meteorological data around the site are inputted.

In this case study, a linear dose-response relationship is assumed as is usually done in an ordinary LCA. $\beta_{ED10h,dichlo}$ can be obtained using equation (5.4) (Pennington 2002). To obtain the $\beta_{ED10h,dichlo}$, NOAEL must be specified. We adopted the NOAEL of chronic toxicity of DCM used in the in-depth risk assessment in Japan, which was to be 92.1 $mg{\cdot}kg^{-1}{\cdot}day^{-1}$ determined by animal testing (Nakanishi and Inoue 2005). For the extrapolation of NOAEL, subchronic-to-chronic and animal-to-human conversion factors are adopted as 3.3 and (human to species bodyweight ratio) 1/3, which are adopted in a literature (Pennington 2002). The human equivalent effect dose inducing a 10% response over the background (ED_{10h}) can be estimated using the equation, $ED_{10h} = 1.6 \cdot NOAEL_{human}$ (Pennington 2002). Although the threshold can be set as the reference dose (RfD) calculated on the basis of NOAEL/uncertainties, the threshold was set at 0 in order to evaluate maximum health impacts.

$$\beta_{ED10h-dichlo} = \frac{0.1}{ED_{10h} - \text{Threshold}} = 1.28E - 02\text{risk} \cdot \left(\text{mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}\right)^{-1} \qquad (3\text{-}4)$$

A $DALY_{chronic}$ of 1.535 $DALYs{\cdot}incidence^{-1}$ was obtained from the results of human toxicology assessment in LIME (Itsubo and Inaba 2005), where the calculation is based on the number of chronically ill patients in Japan. The number of exposed workers in the workplace can be obtained by investigating enterprises, and the number of exposed neighbors can be calculated from the population density around the degreasing site.

In plant-specific RA, DALYs of workers and neighbors are evaluated from the actual concentrations in workplaces and the estimated ones in neighborhoods, respectively. Therefore, the obtained values indicate the actual DALYs of workers in metal degreasing and neighbors living around the site. The DALYs evaluated by plant-specific RA are represented as $DALY_{actual}$ hereafter.

In addition to $DALY_{actual}$, MOE (US-EPA 2008b) can be evaluated using the same information. MOE is calculated by dividing NOAEL of animal testing by the amount of exposure. Therefore, a small MOE implies a high health risk in humans. The equation for MOE is

$$\text{MOE} = \frac{92.1\,\text{mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}}{\text{Amount of exposure}} \qquad (3\text{-}5)$$

where the amount of exposure is calculated by $PDI_{dichlo,inh}$ and BW. The uncertainties of the applied NOAEL (UF) was 100, indicating latent uncertainties due to the following factors: the species difference between laboratory animals (rats) and humans (10), and the individual differences in humans (10).When MOE is larger than this UFs, the risk is regarded as sufficiently low.

MOE has been applied for the in-depth risk assessment of substances (Nakanishi and Inoue 2005) to identify which substances have non-negligible risk in Japan. A separated uncertainty enables decision makers to identify the risk with the uncertainty and to make a decision on the basis of the indication by comparing MOE with UFs (Nakanishi and Inoue 2005; Hirai et al 2006).

Life Cycle Assessment

LCA is performed to quantify the environmental impacts associated with a metal degreasing process. For this purpose, the functional unit of LCA is defined as "daily running of the metal degreasing process", or in a more quantified definition, "300 kg-product precisely cleaned per day". Although there may be various functional units for cleaning (Finkbeiner et al. 1997; Ruhland et al. 2000), the metal degreasing function can be based on the quantity of production, because the alternative technologies taken into account exclude the substitutions of cleansing agents, which means that the quality of metal degreasing can be regarded as the same in all scenarios.

The system boundary is defined on the basis of the life cycle of a cleansing agent as shown in **Figure 3-14**. The detail of LCI is same as that in the subsection 3.3.3 Case Study: Running Process Assessment.

Human health was selected as an end-point impact category to compare the results of the plant-specific RAs of occupational and neighborhood risks. As the LCIA method, LIME (Itsubo and Inaba 2003, 2005) was adopted, because it has been tailored for LCA in Japan. DALYs were used to quantify human health. The DALYs obtained by LCA are marginal owing to an increase in chemical concentration due to the inventoried emission. This is why the DALYs of LCA are represented as $\mathrm{DALY}_{\mathrm{marginal}}$ in the following sentences to separate them from $\mathrm{DALY}_{\mathrm{actual}}$. Global warming and human toxicity are considered mid-point impacts leading to human health. In this regard, however, the available impact factors for human toxic chemicals are the total of carcinogenic and non-carcinogenic impacts. The inventoried emissions for calculating these impacts are available in existing databases (JLCA 2008; JEMAI 2005): carbon dioxide, methane, hydro-fluorocarbon, nitrous oxide, sulfur hexafluoride and dichloromethane.

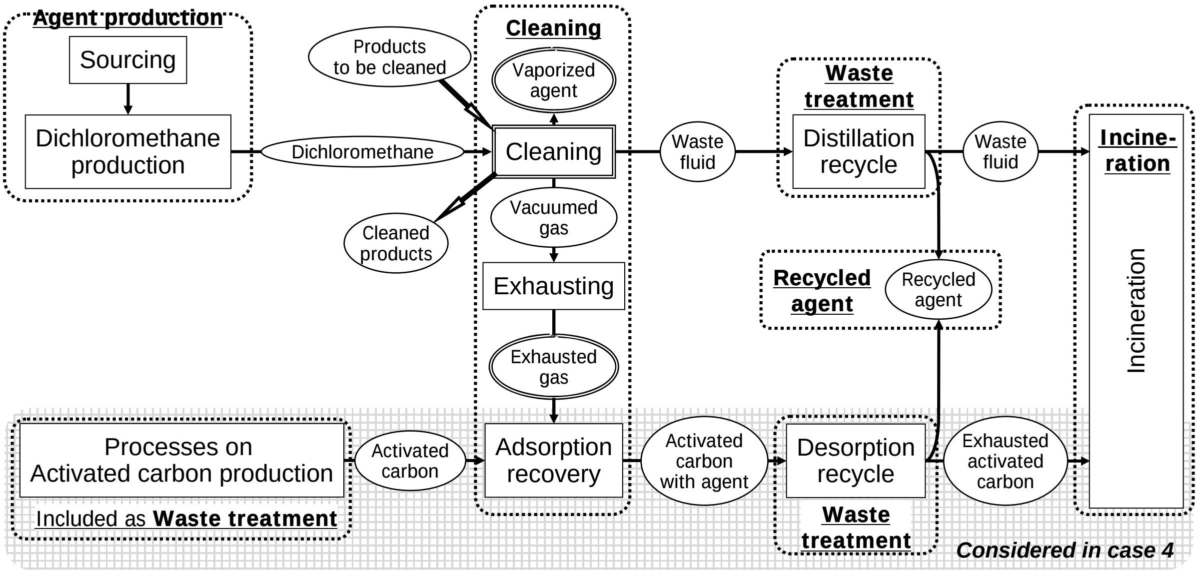


Figure 3-14 Life cycle of dichloromethane in the base case and cases 1 – 4. Production processes of activated carbons are categorized as waste treatment because their environmental loads are from the recycling of dichloromethane. Recycled agents can be fresh cleansing agents at the cleaning site. Therefore, the environmental loads that produce the same amount of recycled dichloromethane are saved.

Feasibility Assessment

This case study focuses on the economic feasibility of each alternative scenario. A simple investment analysis is executed by comparing initial and running costs. Especially, the payout time of investment is analyzed for each alternative.

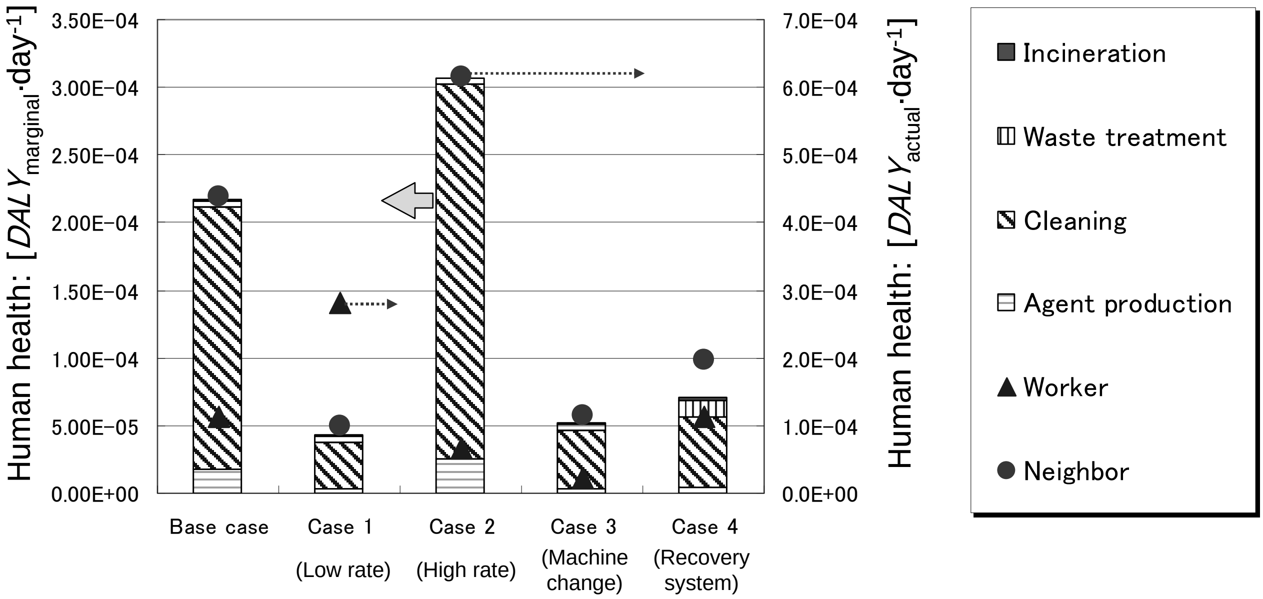
Results

Reference flows and the workplace concentration of dichloromethane are organized in **Table D-8**. These were obtained from the measurements of the site or the empirical data obtained in industries.

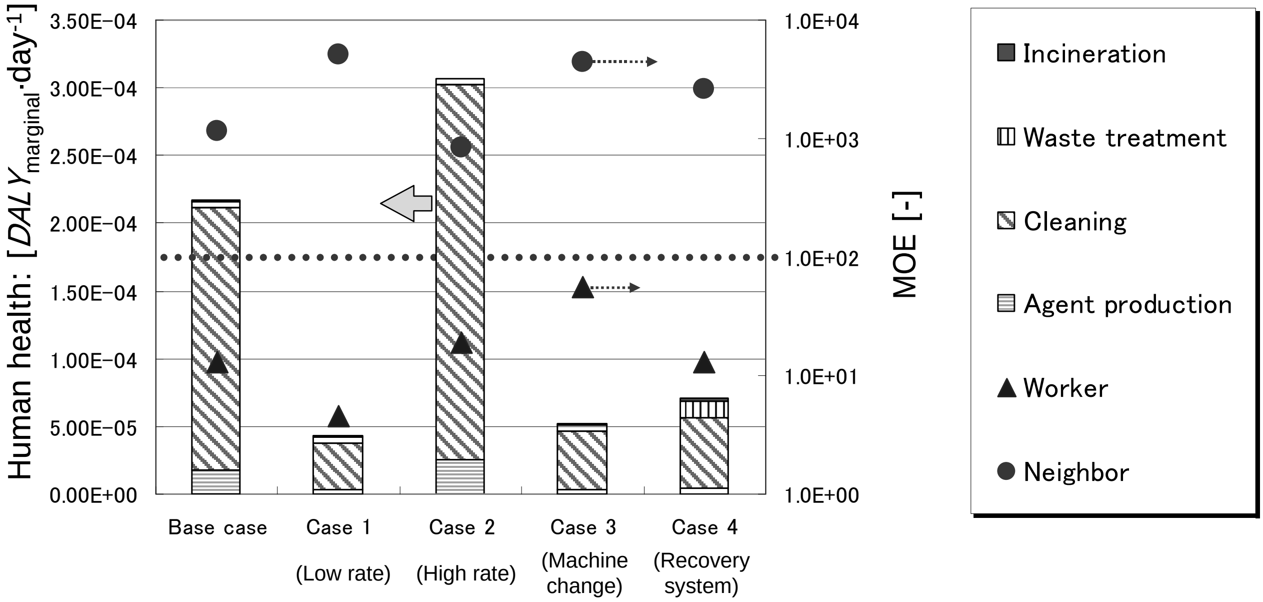
The workplace concentrations, except that in case 1, is below the standard control concentration. In case 1, turning off the local ventilation system is not sufficient for keeping the workplace safe. Although a decision maker cannot select case 1, the results indicate the applicability of decreasing the ventilation rate, because the amount of DCM used in case 1 is markedly smaller than that in the base case. This means that the decrease in ventilation rate can reduce the loss of dichloromethane. **Figure 3-15**-(a) shows the $\mathrm{DALY}_{\mathrm{actual}}$s of workers and neighbors and the $\mathrm{DALY}_{\mathrm{marginal}}$s obtained by LCA with LIME. The contributions to health impacts originated in the emissions of green house effect gases and human toxicity chemicals are shown in **Figure 3-16**. In all scenarios, the neighbors' health risk indicates the same tendency as the $\mathrm{DALY}_{\mathrm{marginal}}$. This is because it mainly depends on the agent exhausted by the ventilation system and almost all DCM is emitted directly into the air by local ventilation. However, the occupational risk indicates a different tendency. This means that the change in workplace concentration does not completely correspond to the change in inventoried emission volume. The $\mathrm{DALY}_{\mathrm{actual}}$s obtained by plant-specific RA are at almost the same order of magnitude of the $\mathrm{DALY}_{\mathrm{marginal}}$s obtained by LCA which includes the $\mathrm{DALY}_{\mathrm{marginal}}$ attributable to green-house-effects, human carcinogenic and non-carcinogenic emissions. This means that local risks should be regarded as a significant evaluation index on human health. **Figure 3-15**-(b) illustrates the MOEs of workers and neighbors and the $\mathrm{DALY}_{\mathrm{marginal}}$ obtained by LCA with UFs value. While all occupational risks could not be reduced sufficiently in all scenarios, the neighborhood risks are at safe levels even in case 2.

Cases 1 and 2 demonstrate the trade-off relationship between an occupational risk and the human health damage due to global impacts. Although the $\mathrm{DALY}_{\mathrm{marginal}}$ in case 1 is much smaller than that in the base case, the $\mathrm{DALY}_{\mathrm{actual}}$ of workers is markedly larger than that in the base case. In contrast, although the worker $\mathrm{DALY}_{\mathrm{actual}}$ in case 2 is smaller than that in the base case, the $\mathrm{DALY}_{\mathrm{marginal}}$ in case 2 is extremely larger than that in the base case. These are due to the flow rate of the local ventilation system being strongly related to the disturbance of the agent in the washing machine as well as the preservation of a safe workplace concentration. If the flow rate is increased, the amount of workplace exposure decreases instead of increasing the amount of the cleansing agent being emitted into the air.

In case 3, the enclosed-hood type ventilation system could reduce the use of DCM, as shown in case 3. All DALYs in case 3 are smaller than those in the base case. This means that residual vaporized agent could be sufficiently emitted into the air with a small disturbance of the agent in the washing machine. The recovery system installed in case 4 could also reduce the emission of the vaporized agent to the air from the cleaning site. However, it could not reduce the workplace concentration, because the recovery system is installed at the end of the ventilation pipe, and also, it could recover only the vaporized agent released directly into the air by the ventilation system.

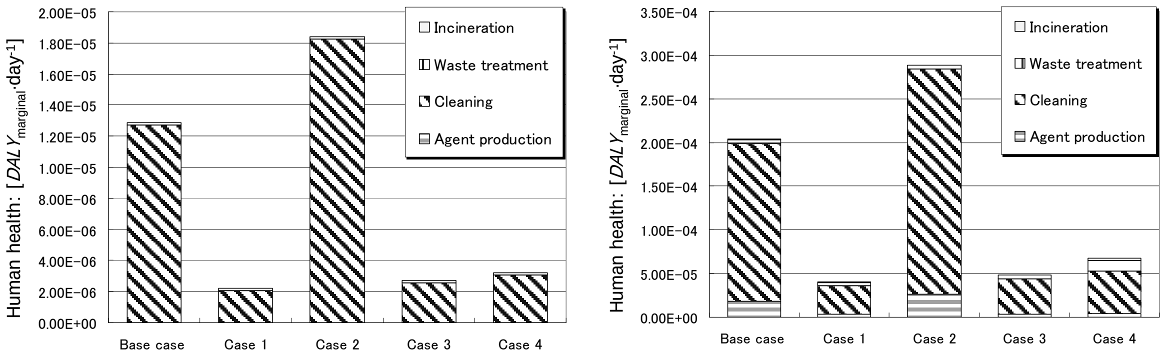


(a) Local: $\text{DALY}_{\text{actual}}$s, Global: $\text{DALY}_{\text{marginal}}$s



(b) Local: MOEs, Global: $\text{DALY}_{\text{marginal}}$s

Figure 3-15 Evaluation results for local and global impacts, which are represented as scatter plots and bar graphs, respectively. Local impacts are represented as the $\text{DALY}_{\text{actual}}$s or MOEs of workers (2 persons) and neighbors living within an area of 1km2 around the cleaning site (7,206 persons). Global impacts are evaluated using the $\text{DALY}_{\text{marginal}}$s of overall population in Japan obtained by LCA with LIME attributable to green-house-effects, human carcinogenic and non-carcinogenic emissions. A small MOE implies a high health risk in humans. The UFs value of utilized NOAEL is 100.



(a) DALYs originated in
human toxic chemicals

(b) DALYs originated in
green house effect gases

Figure 3-16 DALYs originated in global warming and human toxicity

Figure 3-17 shows the payback time of investment for each alternative scenario. Because case 1 has no initial cost, the decrease of running cost leads to cost down of manufacturing parts. In the contrary, case 2 increases the cost, because of the increase of agent consumption. Cases 3 and 4 with the investments in the installation of devices demonstrate that the payback times are 9 and 23 months, respectively. These results should be interpreted with the evaluation results of local risks and global impacts, which are discussed in section 4.6 Risk Interpretation on Available Results.

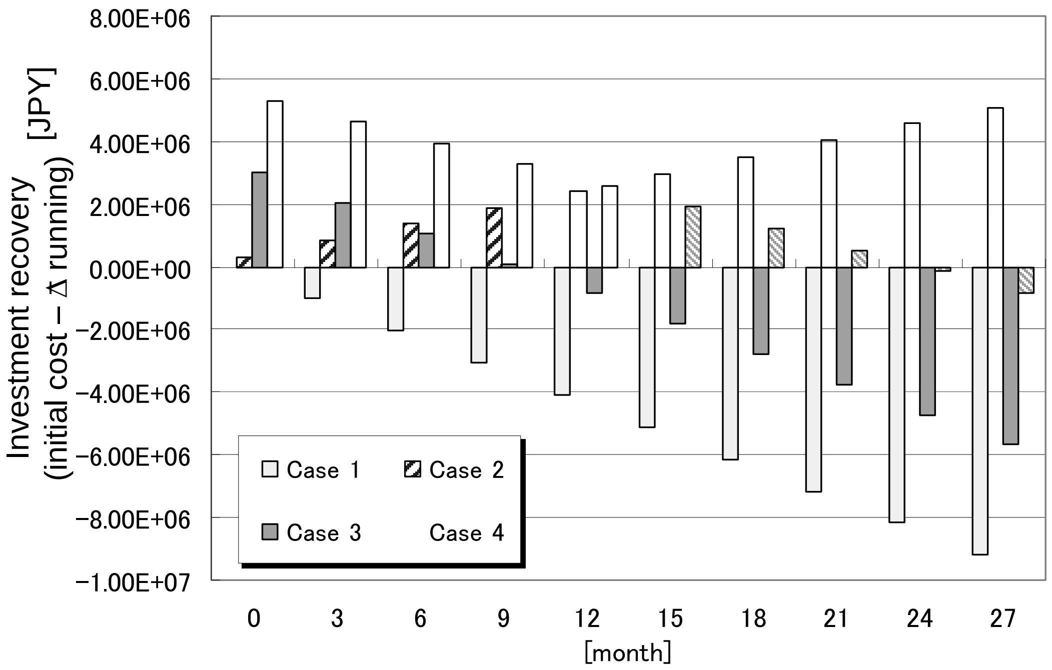


Figure 3-17 Economic feasibility assessment: investment assessment

3.3.5. Conclusion

Risk Evaluation in Metal Cleaning

Local risks and global impacts attributable to metal cleaning processes can be evaluated by integrated application of existing assessment methodologies. This was quantitatively demonstrated in the case studies addressed in the sections 3.3.3 for running processes and 3.3.4 for alternative candidate ones for the chlorinated cleansing agents. In addition to the applicability of existing methodologies, especially in running process evaluations, the several investigations on actual cleaning sites revealed that all required technical data can be available and obtained by on-site engineers. It means a high practicability on data collection by on-site engineers in cleaning processes to execute LCA and plant-specific RA.

Safety risk occurred around cleaning processes is one of the categories to be dominant concerns for on-site engineers, which are mainly cause by hydrocarbon, alcohol and alkaline detergent. Quantification of such safety risks needs several complicated probability analyses about fault and failure leading to them. Because of the lack of technical databases organizing accidental instances on cleaning processes, the implementation of probabilistic analysis might not be practical in the risk evaluation by on-site engineers. However, if there was the simple guideline of checking the daily operation and storing workers' experiences on risks, that is so-called *hiyari hat* analysis, the semi-quantitative analysis would be possible in a site. Such accumulation of daily experiences on risks should be diffused in industrial cleaning.

Risk Reduction in Metal Cleaning

The results of the case study indicate that the emitted dichloromethane has a significant contribution to the local and global impacts associated with its complete life cycle. Although the importance of reducing solvent emissions for risk reductions in metal degreasing could be confirmed, the results cannot easily be interpreted for decision making. The results shown in **Figure 3-15**-(a) indicate the trade-off relationship between local and global impacts. If the evaluated risks are interpreted in more detail, according to the results shown in **Figure 3-15**-(b), the neighborhood risks can be considered as negligible in all scenarios, because the MOEs are below the UFs. The same results can be obtained when the threshold in equation (4.4) was set as RfD, because the MOEs below the UFs indicate that the effect by the dose can be recovered by curative power of human. In addition, if the workplace concentrations of dichloromethane that are lower than the legal level are sufficient for risk reduction, the workers' health risks, except for case 1, can also be regarded as negligible. Hence, these can result in decision making by focusing on only $\mathrm{DALY}_{\mathrm{marginal}}$.

The final decision depends on the subjective criteria of decision makers, who are on-site engineers in this paper. By considering the fact that occupational and neighborhood risks are the major concerns of the decision makers, the local risks should be identified and evaluated meaningfully for decision making.

In the evaluation of human health impacts by human toxic chemicals, the indicators to be interpreted at risk-based decision making should be carefully adopted and compared each other considering what they quantify actually. In this case study, the order of $\mathrm{DALY}_{\mathrm{actual}}$s of workers and neighbors are the same as that of overall $\mathrm{DALY}_{\mathrm{marginal}}$s as shown in **Figure 3-15**, which is the sum of $\mathrm{DALY}_{\mathrm{marginal}}$s originating in global warming and human toxic chemicals shown in **Figure 3-16**. Global warming has the main contribution to the overall $\mathrm{DALY}_{\mathrm{marginal}}$, because dichloromethane has ten times as large global warming potential as carbon dioxide. At the same time, $\mathrm{DALY}_{\mathrm{actual}}$s have larger magnitude than $\mathrm{DALY}_{\mathrm{marginal}}$ originating solely in the emissions of dichloromethane as a human toxic chemical (see also **Figure 3-15** and **Figure 3-16**). For decision making on the viewpoint of human toxicity, $\mathrm{DALY}_{\mathrm{actual}}$s should be compared with $\mathrm{DALY}_{\mathrm{marginal}}$ originated in human toxic chemicals shown in **Figure 3-16**-(b) to exclude the damages except human toxicity.

Differences Between Plant-specific RA and LCA

The main difference between plant-specific RA and LCA is the technical data used to calculate the PDI in equation (5.3). By specifying the plant, decision maker and exposed humans, plant-specific RA can utilize the detailed process data, such as the measured workplace concentrations and local conditions in the ambient surroundings, as well as the inventory data normally used for an ordinary LCA. From such detailed process data, plant-specific RA can evaluate local risks occurring in a situation more actual than that of an ordinary LCA. The concentrations used are actual one including both the background and the increase due to the operational changes or applied devices. Therefore, actual human health risks can be calculated and referred for screening or comparing of alternative scenarios. In this regard, however, the local risks should be judged carefully because they are an immediate threat for a decision maker. This indicates that MOE may be more helpful than DALY as an indicator for screening, because the results represented by MOE can be judged by comparing them with UFs. This enables a decision maker to identify whether the local risks are acceptable using their expertise. On the other hand, LCA can assess the human health on the basis of the different environmental impact categories using large-scale and multimedia models. By such fate models, results indicate the marginal increase in the concentration in the environment due to emissions. By fate analysis, LCA can provide marginal DALYs in the life cycle, which are smaller than the actual DALYs of local risks in the case study about human toxic chemicals. While plant-specific RA may be suitable for the rigorous assessment of the risks occurring around decision makers, potential impacts accompanied by a decision can be visualized in LCA.

Benefits and Requirements of Enhancing the Practicability of Incorporating Both Local and Global Impacts into Actual Decision Making

Actual decisions must be made under various constraints, such as those related to local regulations, budget and targeted risk reductions. Risk communications with workers and neighbors should be considered for plants in residential areas. From the viewpoint of an on-site engineer, local risks should be evaluated in detail and interpreted more intensively than global impacts. The required process data of their own plants, at least about running processes, are available. This indicates that a rigorous risk assessment of a plant and its ambience is sufficiently practicable for a decision maker. In addition to local risks, global impacts have become a public concern. LCA is a powerful tool for validating the performance of environmental management. Thus, the evaluations of local and global impacts are beneficial activities for actual risk-based decision making. Due to the difference in motivation between local and global impact assessments, these impacts should be treated separately, but simultaneously. On the other hand, there are needs to integrate local and global impacts, for example, in evaluations for policy making. In this case, an evaluation should include the occupational and neighborhood risks around all processes in a life cycle. To incorporate occupational and neighborhood risks, the local concentrations must be estimated by using emission volumes, which are typically the only available data in an ordinary LCA. In this regard, however, the uncertainties of estimations become a critical factor of miscalculation, because local risks are considerably sensitive to process data. Thus, for a decision of process design by on-site engineers, the local risks occurring around decision makers are not suitable to be evaluated in the ordinary framework of LCA, because the decision makers can collect and utilize the more accurate process data on their own processes. In this case, such local risks should be separated from LCA. A method of selecting appropriate evaluation methodologies and its practical execution by a decision maker should be discussed in a future work.

Integrated Procedures

Figure 3-18 shows the integrated procedure of different assessments. The definition of objectives and data collection are defined separately from the executions of assessments. This structure enables the transparent and complementary assignments to each methodology and effective data sharing with each other. Such assignments and data collections are discussed in sections 4.2 Risk Specification Based on Scientifically- and Practically-Validated Logic and 4.4 Process Modeling for Assessments of Local Risk and Global Impact, respectively. Interpretation of evaluation results should attribute to the activity of alternative generations and risk interpretation, which are discussed in sections 4.3 Risk-Based Generation of Alternative Candidates and 4.6 Risk Interpretation on Available Results, respectively.

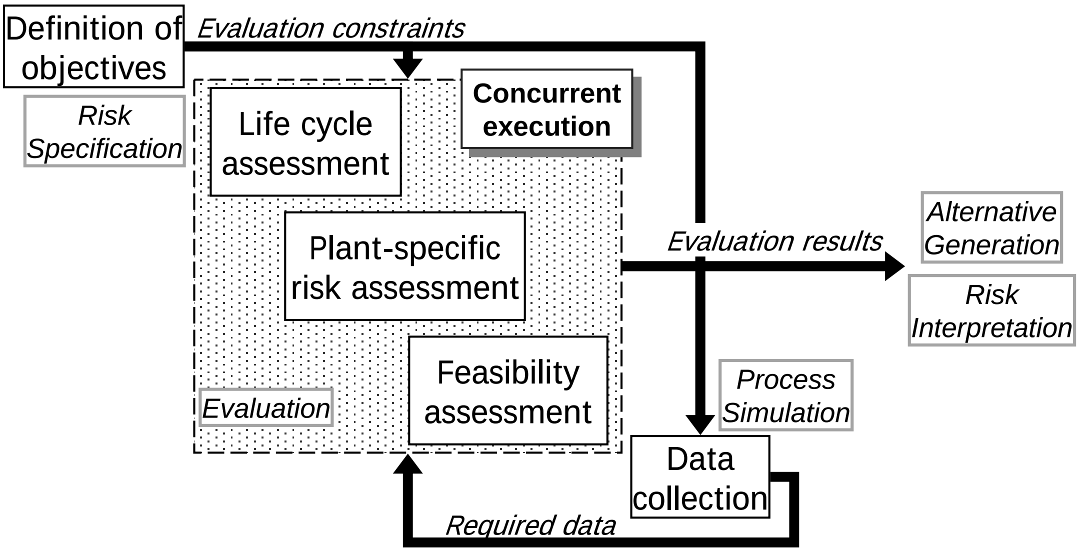


Figure 3-18 Integrated process evaluation

Chapter 4. Knowledge and Technology on Process Design and Evaluation

4.1. Introduction

In the previous chapter, the aspects of problem in the design of metal cleaning process was identified, and then, scientific methods of evaluation were associated as a solution for the problems. The systematized knowledge on process evaluation is the most dominant phase, which varies the following phases significantly, because the evaluation method is the objective function for process design. As well as the evaluation knowledge, related knowledge is required for risk-based decision making. It has been addressed in some fields such as process design and policy making. As the procedures of retro-fitting design to reduce risk originating from a decision, evaluation of running process, alternative candidate process generation, evaluation of alternative process, and making a decision might be considered. The evaluation indices should take into account the main objective function, which may be given unclearly such as "the reduction of major risk". Based on the evaluation results of running process, alternative candidate processes should be generated with logical possibilities to reduce the risk. To evaluate the alternative candidates, which are not exist, data acquisition must include the estimation on process simulation models. Finally, on-site engineers comprehensively interpreted the risk under individual constraints. In each phase of the process improvement, an adequate and elaborate method should be available on the viewpoint of researchers, before discussing the enhancement of practicability by actual decision-makers.

This chapter presents the knowledge on process design and evaluation. Association of knowledge is extended for the other knowledge required for performing the associated knowledge on process evaluation in Chapter 3. The method includes a volume of knowledge we can acquire from existing researches and novel one proposed in this chapter.

Extension of Association from Evaluation to Systematic Design Knowledge

Especially in industrial process design, local risk is the biggest concern for on-site engineers. In spite of such concerning on risk by on-site engineers, risk cannot have been evaluated in comprehensively, because there are various aspects of risk and methods along the characteristics. Towards the risk management in practice, on-site engineers should be able to supervise the risk attributable to their own processes by adequate evaluation methods. In a plenty of assessment methodologies, however, effective selection of suitable one is difficult, but inevitable, on practicability without structured knowledge on evaluation. Moreover, process simulation might be necessary for solving a problem on risk-based decision making. Strongly collaborated assessments and process models are inevitable for the enhancement of the practicability of risk-based decision making.

Figure 4-1 shows process improvement procedure, which includes two process evaluation phases for process in use and alternative candidates. At each design phase, applicable knowledge has been developed in each field of study as fundamental technologies. Such knowledge should be systematized appropriately and discussed in each section of this chapter.

At the time of the association of each knowledge, the networks between units of knowledge must be considered. It enables the extended association based on evaluation knowledge. **Figure 4-2** shows the concept of knowledge network among mechanisms for risk-based decision making. All knowledge on process design and evaluation can be divided into five knowledge units: mechanisms of risk specification (RSM), evaluation (EvM), alternative generation (AGM), process simulation (PSM), and risk interpretation (RIM). The information flows between them are required for the appropriate risk-based decision making. For example, the alternative generation not changing process data used in the evaluation can be meaningless in risk-based decision making. In contrary, the evaluation results can expand the range of possible alternatives reducing risk by the recommendation of additional evaluation indices and indicators, which have not been included in the premises of decision maker. The interdisciplinary structured knowledge can generate unexpected alternative candidates.

EvM is associated in Chapter 3. The following sections present the mechanisms for other knowledge on process design and evaluation. Some existing methods are combined and associated into systematized knowledge as novel mechanisms. At the association, the connection among the five categories of knowledge is carefully addressed for the extended association, which means the development of structured knowledge on process design and evaluation.

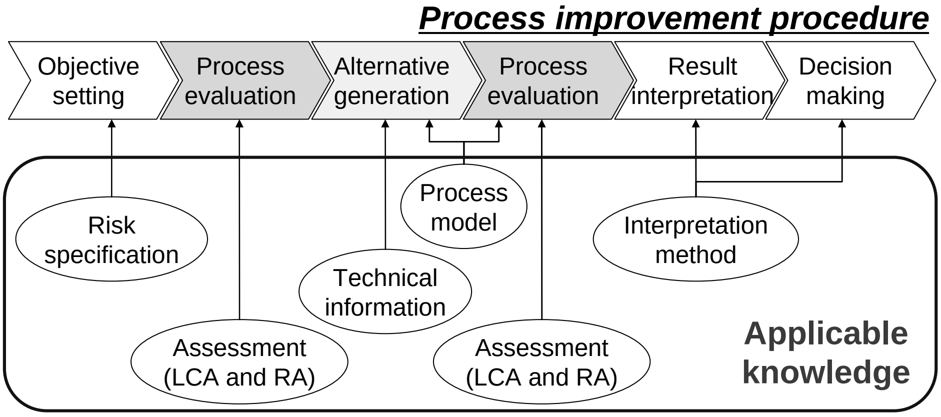


Figure 4-1 Applicable knowledge along with process improvement procedure

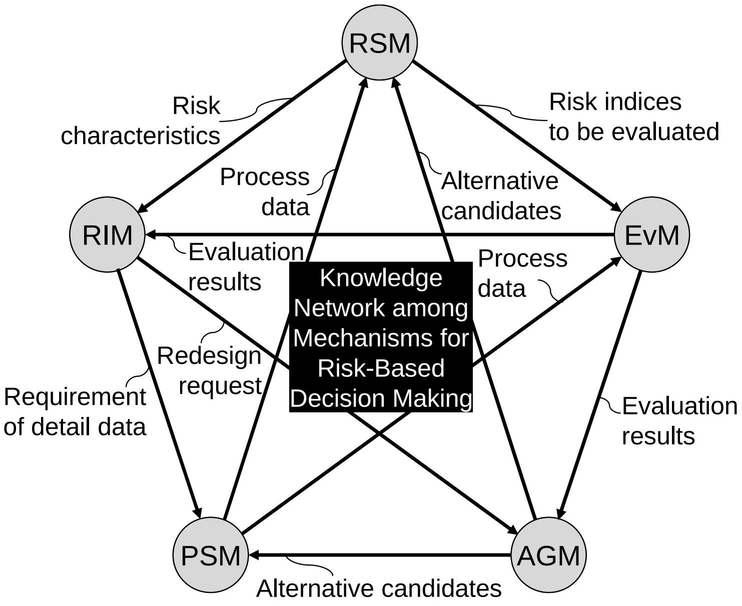


Figure 4-2 Knowledge network among mechanisms for risk-based decision making

4.2. Risk Specification Based on Scientifically- and Practically-Validated Logic

4.2.1. Introduction

To evaluate local risk and global impact accurately by the method proposed in the previous chapter, the decision of risk indices and indicators should be granted a great responsibility in the phase of the definition of objectives in **Figure 3-18**. The inadequate decision of them might result in the incorrect assessment for risk-based interpretation, which directly affect a final decision. A method of selecting and validating such items should be elaborated to take into account scientific reasons and practical conditions of a process and decision maker.

Several researches have been reported on the quantification methodologies of the adverse effects due to the use of chemical substances (Hofstetter et al. 2002). Such assessments can be mainly divided into two types of assessments, hazard and risk assessments. Because chemical hazard can be specified by the used substances, hazard assessment is an effective tool in the early process design phase (Koller 2000). In order to take into account the process characteristics, however, risk assessment should be conducted anywhere in process design.

Theoretically, the risk indices to be evaluated on a process should be considered through the examination of all utilized chemicals, their usages and process input/output data in the life cycle of such chemicals. A number of indicators proposed in developed assessments such as LCA and RA are applicable for the quantification of local risk and global impact. In this regard, however, these indicators include many approximations under several assumptions for achieving quantification (ISO 2000a; Itsubo and Inaba 2005; Hofstetter 1998). Poor understandings of such premises of indicators might result in a misleading of adverse effects originating from a process, and then, the increase of risk.

To avoid such serious mistakes, evaluators should be able to identify and characterize the risk indices that are caused by the evaluated process and to recognize adequate evaluation indicators. A logical algorithm of such activities, which is defined as *risk specification*, should be developed to reduce chemical risk associated with a decision appropriately.

When a number of indicators may be applicable for a risk index, the selection of indicators owes all to the decision by evaluators, who may not be experts in the field. There should be a priority level of indicators to be selected. Such level may be derived from the reliability, data availability, and balance with other risk indices. In associating the knowledge on assessment methodologies, the level should be considered.

This subsection proposes risk specification method aiming to identify and characterize possible risk indices in a process, and to recognize adequate risk indicators. The method is proposed with two components. The first component is a general algorithm for risk specification, and the second is the structure of databases on chemical substances represented as a matrix. This matrix can distinguish risk indicators by visualizing the differences of premises and the meaning of results. It needs the association of knowledge on assessment methodologies. Consequently, the developed method will transcend and connect different assessment methodologies each other for a risk evaluation. In addition to such interconnections of assessments, the recommendation levels of the indicators are defined and incorporated into risk specification.

4.2.2. Algorithm of Utilizing Associated Knowledge

Figure 4-3 shows the outline of the flow chart describing the procedure of proposed risk specification. Idealy, specification should include the all-hazardous properties attributed to the all-chemical substances utilized in the all life cycle stages related with a process. This is why the procedure shown in **Figure 4-3** includes repetition processing of identification and characterization of possible risk indices on life cycle stage (LS), input/output chemical (Ch) and hazardous property (HP). For each possible risk index, risk indicators are recognized and selected from available evaluation indicators (EI), and then, the feasibility of its evaluation are judged by users on the availability of technical data (TD). The procedure where user input is required is located in the repetition processing of TD. User should give approval on whether the TD(m,l,k,j,i) is accepted or not. TD(m,l,k,j,i) means TD(m) to calculate EI(l) attributable to HP(k) of Ch(j) at LS(i).

The procedure shown in **Figure 4-3** composes of quite simple retrieval and screening by user's input. Relational databases on hazardous property, evaluation indicator, and technical data have a big responsibility to enable the risk specification. The way of storing the information on them is one of the indispensable component of development in the field of concerning local risk and global impact. The following is the explanation of each step.

Development of Life Cycle Model (LCM)

This step is the same as one that has already been executed in the researches on LCA, which develops LCM of related process chemical and raw material included in reference flows. Information on the modeled life cycle stages are stored on LS(i), where i: the number of life cycle stages (1, 2, 3, ····· NLS).

Inventory Collection

Based on the developed LCM, the inventories of the input/output chemical substances at LS(i) are investigated by the existing databases. Information on the inventoried chemicals are stored on Ch(j,i), respectively, where j: the number of chemical at LS(i) (1, 2, 3, ····· NCh).

Retrieval: Hazardous Property, Evaluation Indicators, and Technical Data Requirement

For each inventoried chemical substance, information on HP, EI, and TD are retrieved from relational databases proposed in the following subsection. Retrieved information is stored on HP(k,j,i), EI(l,k,j,i), and TD(m,l,k,j,i), respectively, where k: the number of HP of Ch(j,i) (1, 2, 3, ····· NHP), l: the number of EI representing the possible risk caused by HP(k,j,i) (1, 2, 3, ····· NEI), and m: the number of TD required for the calculation of EI(l,k,j,i) (1, 2, 3, ····· NTD). The relational databases stores each information as well as its recommendation level, which decide the order of retrievals of them. Additionally, it is beyond the ordinary databases on them with respect to the detail and accuracy of the definition of information.

Approval by User

The procedures shown above can be automatically subroutines, if the information system is maintained. With regard to the final judgment, however, user should intervene the processing of risk specification. According to the retrieval procedure, HP, EI, and TD are ordered on the accuracy of the evaluation results by the recommendation levels defined and stored in the relational databases with each information. The order of approval requirements are along with that of recommendation for a TD. Generally, evaluation that is more accurate needs calculation that is more complicated, that leads data availability of decision maker to be less. Users can decide the acceptance based on their own data availability. If a TD(m,l,k,j,i) is specified, risk index and indicator are specified, simultaneously.

Finalization of Specification at LS

Specified risk indices and indicators are organized with HP and TD. Comparing the specification results each other, that can refer to the retrieval results just after each process, enables the avoidance of redundunt settings of risk indices and indicators.

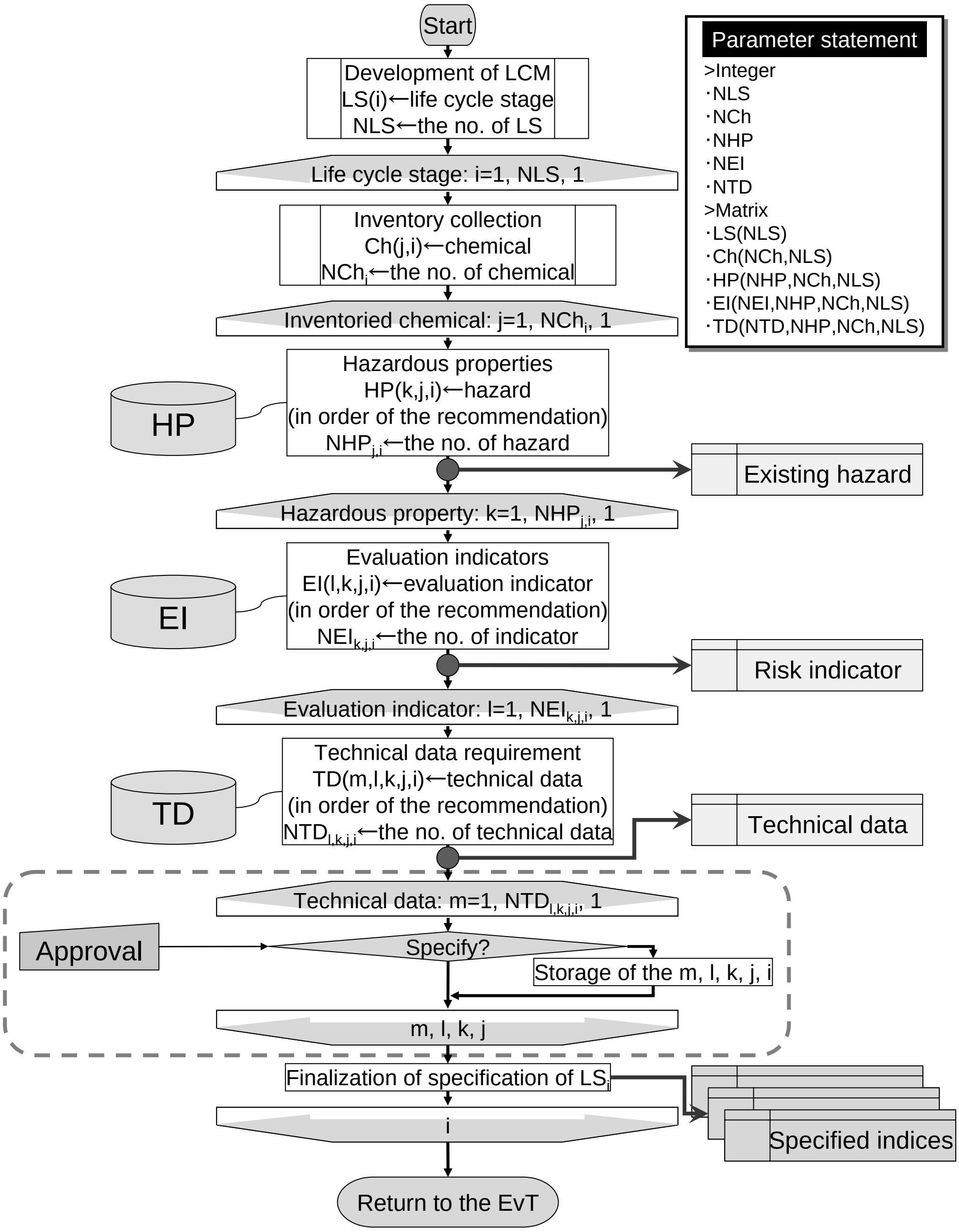


Figure 4-3 Flow chart of a system for risk specification

4.2.3. Association of Knowledge on Risk Index and Indicator

Considerable Risk Features

The advantage of risk specification depends on the relational databases shown in **Figure 4-3**. Effective relation with risk features should be implemented into the way of storing information in databases. Among several features dominating the aspects of risk, the temporal and spatial aspects were regarded as the features determining the evaluation results adequately. They are deserved careful analysis and recognition of the key factor to segregate risk indices on their characteristics.

Temporal Aspects

The temporal aspects of risk can be divided into three categories as follows. This categorization is originated in the characteristics of hazardous property.

- Accidental occurrence in use (incl. short-term occurrence after emission)

The probabilistic and deterministic effects caused during usage or within a day

- Medium-term occurrence after emission

Effects caused by the continuation of causal phenomena for more than a day and less than three months or in three months after emitting causative substances into the environment.

- Long-term occurrence after emission

Effects caused by the continuation of causal phenomena for more than three months or from three months after emitting causative substances into the environment.

*1Probabilistic effect: The increase of a parameter increases the possibility of causing the effects.

*2Deterministic effect: When a parameter is under the threshold, the effects are not caused.

Spatial Aspects

The spatial aspects can be divided into three categories on the basis of the targeted spatial range of calculations in fate, exposure (probability), and effect analyzes in RA.

- Local

The microenvironments that are indoor places where the causative substances are utilized and its ambient surroundings e.g., within 1 km^2 around emission source.

- Regional

A certain range of geographical area with the same climate condition e.g., provinces, nations, and international partitions such as Asia and Europe.

- Global

The area larger than regional range. Because the chemical substances must be diffused to cause such wide scale of impact, accidental impact on global cannot be happened. Moreover, the calculation of impact does not have to consider the geographical difference of emission place for global impact.

Temporal and Spatial Aspects of Data Requirement on Risk

All required information for RA have the temporal and spatial aspects originating from the data sources. The fate analysis of chemical, which are implemented in RA and LCIA method, takes into account several conditions on the diffusion of emissions such as climate conditions, geographical features, residence time, and half-life period. These parameters affect the temporal and spatial aspects of the emission distributions, which affect directly the results of exposure and effect analyses. All parameters utilized in assessments should be considered and classified on their temporal and spatial aspects. However, there is huge number of parameters utilized in an existing assessment. As the available items affected by the temporal and spatial aspects of utilized parameters, HP, EI, and TD are accepted as the factors dominating the evaluation results.

Risk Classification Matrix (RCM)

In order to clarify the difference of aspects, the items should be mapped on a matrix. A matrix is useful to visualize differently categorical items. For the large number of categorization axes, however, the mapping approach is difficult to show the overview of classification. **Figure 4-4** indicates the nine categories classified on the basis of temporal and spatial aspects of risk. This matrix is defined as risk classification matrix (RCM). The item located in the upper left corner of RCM means that its rigorous RA requires the most temporally and spatially details about the usage and emission of chemical. Such rigorous RA requires technical data on the concentration of chemical as well as the amount of emission with temporal profile and other conditions in the microenvironment. In the contrary, for the item in lower right, wider and longer range of information is needed. Although the average data on emission is acceptable in this time, the range of data should be wide up to the whole life cycle of related products.

Figure 4-5 mapped the existing assessment methodologies based on the RCM. RA series have assessed the local risks on the various temporal aspects. Occupational RA focuses on the workplace, which has been conducted by employment medical advisors with special concerns. This is because the workers are exposed to highly concentrated chemicals redundantly. The condition of health risks seems to be different from a general exposure to people. In addition to the occupational exposure, probabilistic RA has been conducted for critical events such as the fire/explosion in plants or accident in nuclear power plants. ERA is one of the tool to quantify serious environmental damages such as ground pollution and local pollution. The assessments of these problems require temporally and spatially detail analysis of the effect-cause chain. LCA has assessed wider and longer impacts than RA as shown in **Figure 4-5**. Although ERA has been implemented into LCIA, the target of assessment is different between original ERA and that in LCIA.

The mapping to RCM can reveal the limitation of applicable range of each assessment methodology i.e., they have the preferable target of evaluation. This means the proposed RCM can be useful to distinguish associate knowledge on risk with assessment methodologies ono their features.

RCMs in Risk Specification

Figure 4-6 shows the overall image of risk specification with RCM. At first, HP existing in a process can be identified by the utilized chemical information. Although existing hazard databases can undertake the role of such identification, proposed risk specification returns the relevant EIs and TDs with HPs. Based on the returned TDs, inquiry sessions are performed to recognize the acceptable TDs, which connect EIs with HPs. The data availability of decision maker is reflected in this recognition process. By going through these procedures of risk specification, four RCMs are formed as shown in **Figure 4-6**: RCM on existing HP, available EI, considered HP, and evaluated EI.

The comparison of available EI and evaluated EI can reveal the data availability of decision maker. If there is a blank in nine cells of evaluated RCM where any available EI occupy, it means that the evaluation might have incompleteness of assessment. This is also true in the comparison of existing HP and considered HP. No considered HP can be revealed by the cells.

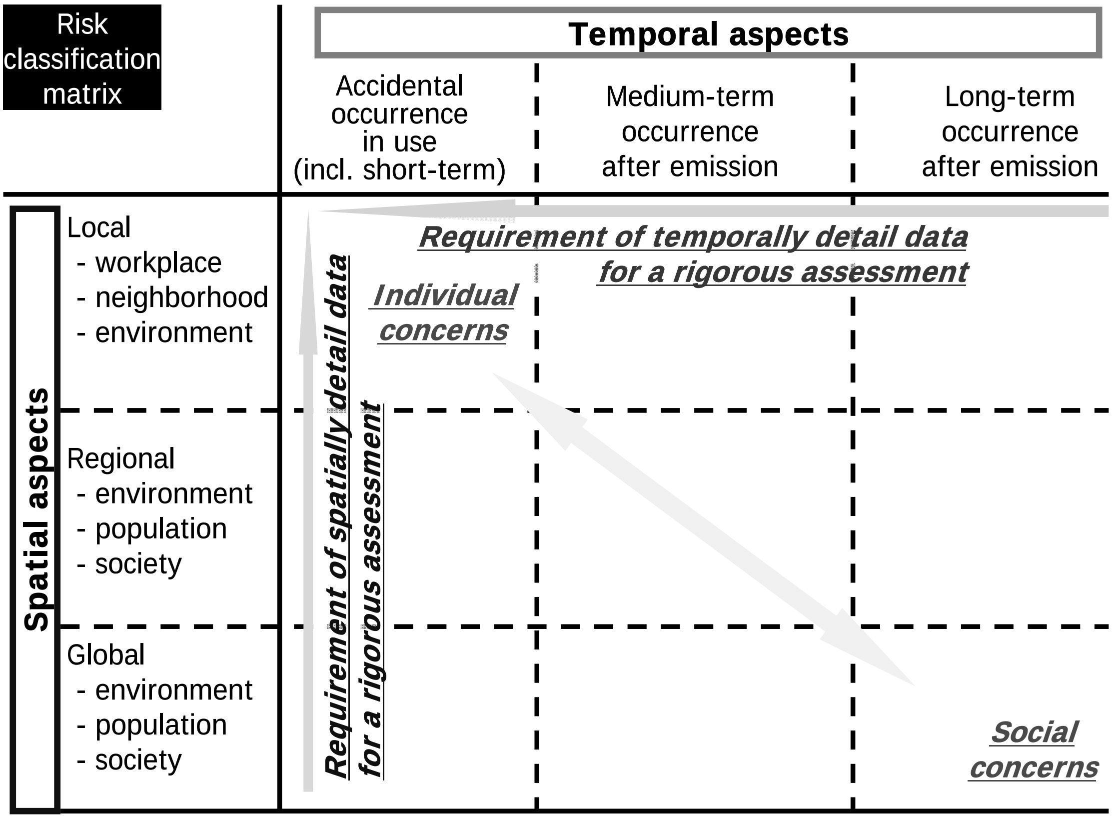


Figure 4-4 Risk classification matrix to structure the knowledge on chemical risks

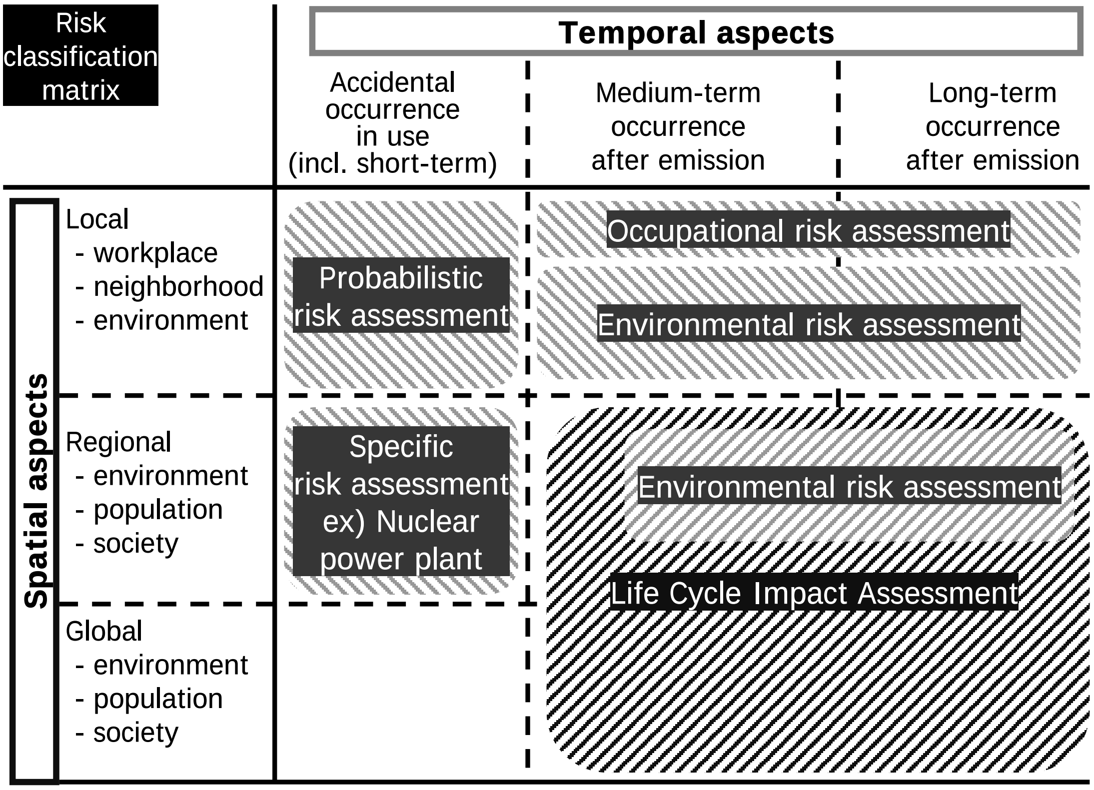


Figure 4-5 Classification of existing assessment methodologies

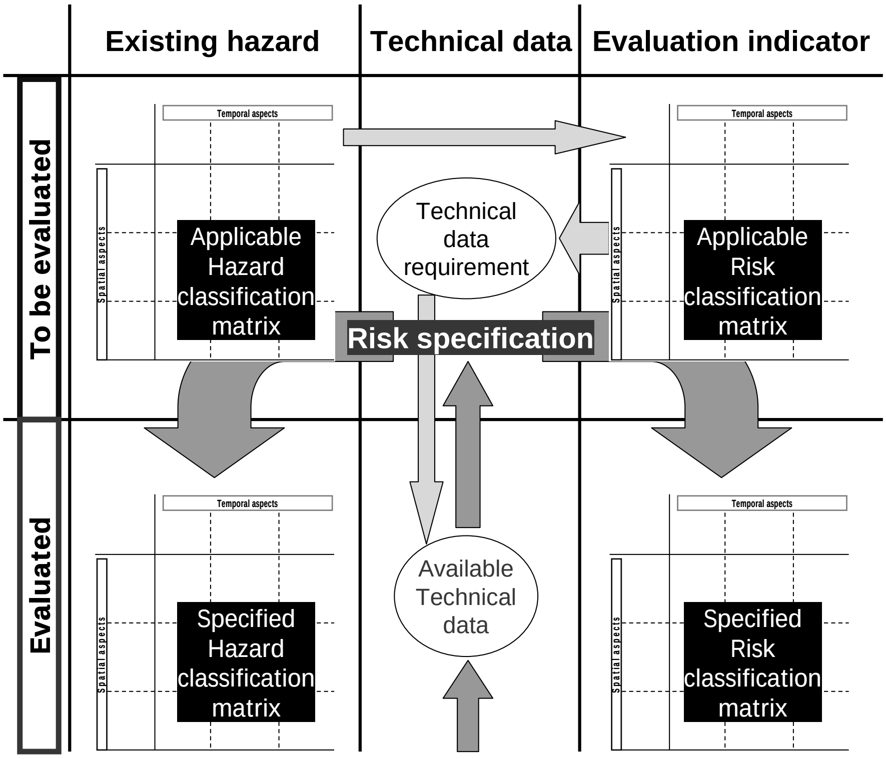


Figure 4-6 Risk classification of hazard, evaluation indicator and technical data

Table 4-1 organizes the classification examples of hazardous properties with the classification reasons. As well as temporal and spatial aspects, the victims of targeted risk are indicated in **Table 4-1**. This classification can be performed by scrutiny on the details of hazardous properties. In a similar way, evaluation indicators can be classified and shown in **Table 4-2** as examples. The all results are organized in **Table 4-3** and **Table 4-4** for HP and EI, respectively.

As shown in **Table 4-3**, there are various types of HPs for a chemical substance. HP regarded as physical property can be simply understood such as flash and auto ignition points. Experimental data absorbs a huge percentage of the HPs in **Table 4-3**, which means the most of HP are obtained by specialist experiments. As well as such measured data, calculated data based on logics and decided data with not only scientific interpretation are included in HPs. Scientific method such as LCIA method can create a kind of HPs in addition to the measured data. The regulation values and labeling can behave as the HPs of chemical substances. Although the uncertainties of these non-measured data are comparatively larger than those of measured ones, some of them are coordinated for the sake of simplification of evaluation. Such dedicated HP can be useful. In this regard, however, the assumptions implemented in the development of such HP should deserve a careful analysis to clarify the uncertainty. Based on the assumptions and conditions of each HP in **Table 4-1**, the RCM on existing HP is organized as **Table 4-3**.

In HPs mapped in RCM in **Table 4-1**, R-phrases are included and has different meaning from other HPs. R-phrases are defined in Annex III of European Union Directive 67/548/EEC: Nature of special risks attributed to dangerous substances and preparations. They are kind of a label on chemical about the risk caused by it. Because it is for the classification of chemicals on risk, there is no value enabling quantitative assessments. R-phrases are the warning about the possible risk. From this fact, it can be considered as the existence of R-phrase indicates the necessity of the evaluation on related risk.

Table 4-1 Classification example of hazardous property

	Temporal aspect	Spatial aspect	Victim
NOAEL $_{\text{animal}}$	Medium/Long	Local/Regional/Global	-
	Experimental condition	Dispersion model utilized in fate and exposure analyses	Experimental animal
NOAEL $_{\text{human}}$	Medium/Long	Local/Regional/Global	-
	Investigation condition	Dispersion model utilized in fate/exposure analyses	Human
GWP (IPCC 4th)	Long	Global	-
	20, 100 and 500 years	Global or half-global magnitude	Site-general environment
OCEF (LIME)	Medium	Regional	-
	·Reaction between a few hours from a day after emitting ·Lasting until the created ozone is decomposed	Defined diffusion geographical division, where the items affecting fate/exposure analyses such as meteorological conditions can be same	Site-specific environment
DALY $_{\text{GWP100, marginal}}$ (LIME)	Long	Global	-
	100 years when the global warming is lasting	Global or half-global magnitude	General population
DALY $_{\text{OCEF, marginal}}$ (LIME)	Medium	Regional	-
	·Reaction between a few hours from a day after emitting ·Lasting until the created ozone is decomposed	Defined diffusion geographical division, where the items affecting fate/exposure analyses such as meteorological conditions can be same	Population in specific area

Table 4-2 Classification example of evaluation indicators

	Temporal aspect	Spatial aspect	Victim
DALY $_{\text{indoor, marginal}}$ (Partly developed in LIME second version) (under development in UNEP/SETAC LC Initiative)	Medium/Long	(microenvironments in) Regional	-
	·Being Caused during the use of chemical ·Same exposure continuance as that of utilized NOAEL	All microenvironments including workplaces and households utilizing chemical within the country	Total population in the spatial aspects
DALY $_{\text{indoor, actual}}$ (to be developed)	Medium/Long	Local	-
	·Being Caused during the use of chemical ·Same exposure continuance as that of utilized NOAEL	Microenvironment including workplaces, households utilizing chemical or neighborhoods around the site	Population in the spatial aspects
MOE (Existing risk assessment reports)	Medium/Long	Local/Regional/Global	-
	·Being Caused during the use of chemical ·Same exposure continuance as that of utilized NOAEL	Flexible definition depended on the target of fate/exposure analyses	Flexible (human health and environment)

Table 4-3 Classification result of available hazardous properties

ALL		**Temporal aspects**					
		Accidental occurrence in use (incl. short-term occurrence after emission)		Medium-term occurrence after emission		Long-term occurrence after emission	
Spatial aspects	Local						
	- workplace	A-I-T, LEL/UEL, FP, STEL, IDLH, ERPG, GK	R1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 30, 34, 35, 36, 37,	TWA, LD50/LC50, LOAEL/NOAEC, LOAEL/LOAEC, MAK	R20, 21, 22, 23, 24, 25, 26, 27, 28, 34, 35, 36, 37, 38, 41, 42, 43, 65, 67	TWA, LOAEL/NOAEC, LOAEL/LOAEC, MAK	R48 with R20, 21, 22, 23, 24, 25, 26, 27, 28, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 45, 46, 49, 61, 63,
	- neighborhood	A-I-T, LEL/UEL, FP	R3, 4, 16, 11, 12, 15, 17	LD50/LC50, LOAEL/NOAEC, LOAEL/LOAEC	R23, 26	LOAEL/NOAEC, LOAEL/LOAEC, MAK	R48 with R23, 26, 33, 39, 46, 61, 63, 64
	- environment	LC50/EC50, NOEC, LOEC		LC50/EC50, NOEC, LOEC	R50, 51, 52, 54, 55, 56, 57, 60, 62	NOEC, LOEC	R53, 58, 68
	Regional						
	- environment			OCEF, AETP;a,w,s., TETP;a,w,s., NOEC/LOEC, NPP-OCEF	R50, 51, 52, 54, 55, 56, 57, 60, 62	DAP, AETP;a,w,s., TETP;a,w,s., EINES-ETP;a,w,s., NOAEL, NPP-AcidP	R53, 58, 68
	- population			DALY-(OCEF, AirPollut.)		HTP_canser;a,w,s., HTP_chronic_dis.;a,w,s., DALY-(HTP;a,w,s., noise)	
	- society			Social resource-OCEF		Social resorce-AcidP,	
	Global						
	- environment			ODP, EPMC, Land_use		GWP;20,100,500., NPP-(ODP, Land_use,natural resorce), EINES-(Land_use, natural resorce)	R59
	- population					DALY-(GWP, ODP)	
	- society					Social resorece-(GWP, ODP, EPMC, natural resorce, waste) Waste volume	1/R-natural resorce

Table 4-4 Classification result of available risk indicators

ALL: EI

Spatial aspects		Temporal aspects					
		Accidental occurrence in use		Medium-term occurrence after emission		Long-term occurrence after emission	
Spatial aspects	Local						
	- workplace	HAZOP, FTA, HQ	Risk, MOE	MOE, DALY_actual	HQ, Risk	MOE, DALY_actual	HQ, Risk
	- neighborhood	HAZOP, FTA		MOE, DALY_actual	HQ, Risk	MOE, DALY_actual	HQ, Risk
	- environment	HQ, Risk, MOE		HQ, Risk, MOE		HQ, Risk, MOE	
	Regional						
	- environment			OCEF, AETP;a,w,s., TETP;a,w,s., NOEC/LOEC, NPP-OCEF		DAP, AETP;a,w,s., TETP;a,w,s., EINES-ETP;a,w,s., NOAEL, NPP-AcidP	
	- population			DALY_marginal-(OCEF, AirPollut.)		HTP_canser;a,w,s., HTP_chronic_dis.;a,w,s.,	DALY_marginal-(HTP;a,w,s., noise)
	- society			Social resource-OCEF		Social resorce-AcidP,	
	Global						
	- environment			Land_use		GWP;20,100,500., NPP-(ODP, Land_use,natural resorce)	EINES-(Land_use, natural resorce)
	- population					DALY_marginal-(GWP, ODP)	
	- society					Social resorece-(GWP, ODP, EPMC, natural resorce, waste) Waste volume	1/R-natural resorce

4.2.4. Recommendation of Risk Indices and Risk Indicators

Risk Indices

A huge number of possible risk indices can exist even in a process utilizing a few chemical substances because a chemical substance has many HPs in various risk categories. Although all risk indices should be taken into account to the evaluation of process ideally, it is not feasible to execute all risk evaluations. The full set of risk evaluation may not be effective, as well. For example in cleaning process, most chlorinated solvents has explosion limits, and explosion risks should be considered in process operation. However, there was little possibility of explosion in cleaning process, which can be proven by the fact that few explosion accidents have been reported so far. According to another fact that the actual operator does not pay attention to the explosion by chlorinated solvents, safety risk has not been reduced by special operation by them. Such risk can be negligible for evaluation. Note that it is no doubtful that process evaluation should include as many risk indices as possible. If it is not feasible, decision-maker should identify all risk indices originating from their own decision. Risk specification should be able to let users recognize possible risk indices without the discussion whether they should perform actual quantitative evaluation.

As the method to specify the risk indices to be evaluated, some approaches are possible and should be discussed. A simple approach is the screening based on the prior occurrences of accidents. The usage of chemical substances is different among the industrial sectors. Occurrence of accidents must depend on such industrial-sector specific conditions. Therefore, if databases storing prior accidents are available, they can be strong supporting information for the specification of risk indices. In this regard, however, no existence of prior occurrence does not mean that the risk index is not needed in evaluation. This approach can indicate risk indices to be evaluated consistently, not ones there is no need to evaluate.

Regulation and label can be other supporting information. Registration and hazardous labeling, for example, risk-phrase by European Committee (EC 2001; CIS 2001) of chemical substances mean comparatively high possibility of the occurrence of related risk indices. Especially, some labels of risk-phrase indicate the high risk possibility such as R3: Extreme risk of explosion by shock, friction, fire or other sources of ignition or R53: May cause long-term adverse effects in the aquatic environment. Such labels can be a criterion to judge the requirements of evaluating related risk indices.

The prior occurrence of accidents and regulated lables can be regarded as the scientific viewpoints for risk specification. As risk specification for sustainability, not only such scientific reasons, but also social reasons should be taken into account. Some environmental impact categories have become issues in public. Such indices were necessitated as the social needs, or public sense of value. The change of the public sense should be addressed in the recommendationn of risk indices.

Risk Indicators

For the appropriate and effective risk specification, HP, EI and TD should be ranked and recommended based on some criteria, which can classify them on its characteristics. **Figure 4-7** shows the three criteria to be taken into account in the selection of HP, EI and TD. These three criteria can distinguish the evaluation on the recommendation level of utilized HP, EI, and TD. The most important item should be physical exactitude. It indicates the correctness and adequateness of evaluation comparing the actual adverse effects caused by chemical substances. Temporal and spatial aspects and victims are the example of attributions of exactitude. RCM shown in **Figure 4-4** is the mapping of this criterion. As well as the physical exactitude, accuracy of evaluation should be considered as one of the dominant criteria for the appropriateness. Accuracy can be recognized as two categories: uncertainty and variability. Both are adherent features for process data, model, and calculation. Although it is impossible to quantify them definitely, the tendency of them on specific HP, EI and TD can be analyzed on the characteristics of each parameter. Based on the magnitudes of them, recommendation should be considered. The third criterion, practicability, has a little bit different aspect from the two criteria mentioned above. Practicability of evaluation strongly depends on the data availability of decision makers. The procedure of risk specification shown in **Figure 4-3** owes it the final judgment of risk specification. It means the practicability of HP, EI, and TD need not to be included in the relational databases, because that of evaluation is considered in interactive system with users.

The recommendation of evaluation should be indicated for each EI. Physical exactitude, practicability and accuracy are changed depending on those of the HP and TD required for the calculation of EI. These aspects should be addressed for each HP and TD. Base on the addressed aspects, EI with HPs and TDs should be demonstrated with the recommendation level, which means the evaluation result of EIs. At this time, it can be based on the relative quantification of the recommendation level. This is because the recommendation scope the selection of EI from available EIs. By setting the most excellent value of each category as 5, the relativities among available EIs can be discussed as follows. In this regard, however, EIs require one or more HP and TD. To compare the each category of recommendation among available EIs, the recommendation level should be normalized.

Physical Exactitude

Physical exactitude of EI depends on that of TD and HP, which are utilized in the calculation of EI. Utilized TD can be divided into two types on the characteristics: extensive and intensive variables of process. It can be recognized as well that there are background and foreground TDs utilized in the calculation of EIs. These classifications of TDs have strong relativities with the physical meanings of EIs. Based on the classifications of TDs, the physical exactitude of EIs should be addressed semi-quantitatively to compare them among available EIs. At that time, the semi-quantification can be considered on the temporal and spatial aspects of adverse effects shown in RCM. As well as TDs, HPs utilized in the calculation of EIs are influential on the physical meaning of EIs. There can be some attributions on original data types of HPs to be analyzed on the RCM: physical property, experimental data, regulation value, and calculated values on general and specific models. Because each data type has original meanings as a HP, the analysis of physical exactitude should take into account the matching accuracy of HP to the target adverse effects.

The calculation needs several assumptions on TD and HP to reduce the variability of them or make up for the lack of data. Such assumptions can lower the physical exactitude of EI. As the assumptions of TD, the aggregated calculations of EI are focused on, because it is often derived from the lack of TD. At the same time, such aggregation can reduce the variability of TD. For the assumptions of HP, the interpolation and extrapolation utilized in the collection of HPs should be taken into account. Theses estimations of HPs can create missing data in hazard researches on novel or complicated chemical substances.

Equation (4-1) shows the recommendation level on physical exactitude (R_Level(E)).

$$\mathrm{R\_Level(E)} = \frac{\left(\sum_{i}^{N_{td}} E_{TD,i} \cdot \prod_{i}^{N_{a,td}} \mathrm{Assum}_{ETD,i}\right) + \left(\sum_{i}^{N_{hp}} E_{HP,i} \cdot \prod_{i}^{N_{a,hp}} \mathrm{Assum}_{EHP,i}\right)}{\max(E) \cdot \left(N_{td} + N_{hp}\right)} \qquad \textbf{(4-1)}$$

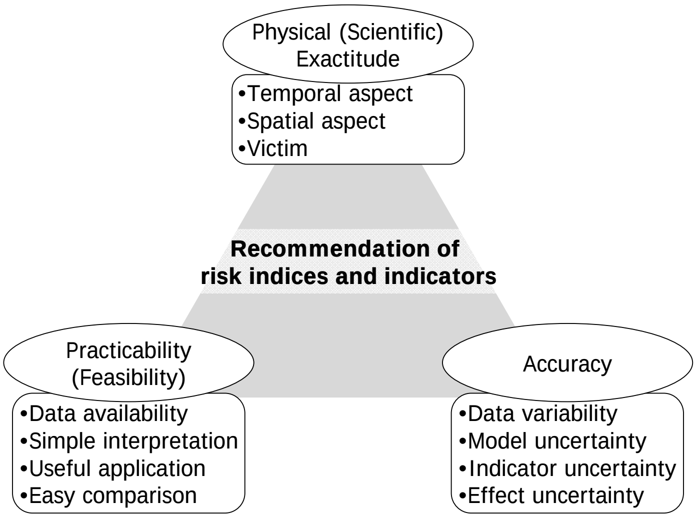


Figure 4-7 Criteria for recommendation of risk indices and indicators

Table 4-5 Scoring rule of physical exactitude value on TD and HP (E_{TD} and E_{HP})

Score	(The utilization of TD or HP for the calculation of EI is)
5	Best suitable representation of target adverse effect
4	Better suitable representation of target adverse effect
3	Possible on the representation of target adverse effect
2	Possible with careful interpretation on the difference against target adverse effect
1	Possible, but not recommended on the representation of target adverse effect
0	Just a trial calculation

Table 4-6 Reduction coefficient of score of physical exactitude by assumption ($Assum_{ETD}$ and $Asssum_{EHP}$)

Reduction coefficient	(The utilization of assumption for TD or HP makes)
0.9	Miner change on the meaning of EI
0.8	Small change on the meaning of EI, but suitable
0.65	Significant change on the meaning of EI
0.50	Different meaning to be interpreted with special attention

where $E_{TD,\,i}$: physical exactitude value of TD_i ($1 \leq E_{TD} \leq 5$, integer), $E_{HP,\,i}$: physical exactitude value of HP_i ($1 \leq E_{HP} \leq 5$, integer), N_{td} and N_{hp}: the number of TD and HP required for an evaluation indicator (integer), $Assum_{ETD,\,i}$ and $Assum_{EHP,\,i}$: the degree of assumption applied in TD_i and HP_i ($0 < Assum \leq 1$), $N_{a,td}$ and $N_{a,hp}$: the number of assumption (integer) and max(E): the maximum value of physical exactitude (5). The scoring rule of the physical exactitudes of TD and HP are organized in **Table 4-5** and the results are in **Table 4-7** and **Table 4-8** for TD and HP, respectively. In this time, the reduction of scores by assumption is included in the results, which are set on the rule shown in **Table 4-6**.

The denominator of **Equation (4-1)** is the maximum sum of the score of physical exactitudes on TD and HP. It means that the calculated value is normalized between 0 to 1 ($0<R\_Level(E)\leq 1$). The first term in the numerator of **Equation (4-1)** means the score of TD, which can be obtained by multiplying the sum of the scores of TDs utilized in EI by the product sum of the reduction rates of applied assumptions in the calculation of EI. In the same way, the second term calculate the score of HP. Each score of TD and HP and reduction rata of assumption are estimated on the basis of relative comparisons referring existing EIs.

Table 4-7 Scores of physical exactitude (E) and accuracy (A) on features of TD

	Extensive foreground data	Intensive foreground data	Extensive background data	Intensive background data
Global/ Long	E:4 A:3-1	E:5 A:1-1	E:3 A:3-3	E:4 A:1-3
Global/ Medium	E:4 A:3-1	E:5 A:1-1	E:3 A:3-3	E:4 A:1-3
Regional/ Long	E:4 A:2-2	E:5 A:2-2	E:3 A:2-2	E:4 A:2-2
Regional/ Medium	E:3 A:2-2	E:5 A:2-2	E:2 A:2-2	E:4 A:2-2
Regional/ Accidental	E:1 A:1-1	E:5 A:1-1	E:0 A:1-2	E:2 A:1-2
Local/ Long	E:3 A:3-2	E:5 A:3-2	E:1 A:1-1	E:2 A:2-2
Local/ Medium	E:3 A:2-2	E:5 A:3-2	E:1 A:1-1	E:2 A:2-2
Local/ Accidental	E:2 A:2-1	E:5 A:3-1	E:1 A:1-1	E:1 A:2-1
Aggregation: Accidental, Medium, Long	E:0.5 A:0.5-0.65			
Aggregation: Medium, Long	E:0.8 A:0.65-0.8			
Aggregation: Local, Regional	E:0.65 A:0.5-0.65			
Aggregation: Regional, Global (incl. site-generic)	E:0.8 A:0.65-0.8			

*E: Score of E_{TD}, A: Scores of Au_{TD} and Av_{TD} (Au_{TD}-Av_{TD})

Accuracy

As the parameters related with accuracy, the uncertainty and variability of TD, HP, and the calculation with them should be taken into account carefully. The more rigorous evaluation needs the more complicated data, which has a possibility to be larger variability even though the availability is high enough. On the other hand, simple data is enough for the simple calculation to reveal the overall tendency of the adverse effects. In this regard, however, the uncertainty of results might exist due to the defect of the physical or statistic models' estimation.

Table 4-8 Scores of physical exactitude (E) and accuracy (A) on features of HP

	Physical property	Experimental data	Regulation value	Calculated value on	
				General model	Specific model
Global/ Long	E:2 A:1-3	E:4 A:1-3	E:2 A:1-2	E:5 A:3-3	E:4 A:2-2
Global/ Medium	E:2 A:1-3	E:4 A:1-3	E:2 A:1-2	E:5 A:3-3	E:4 A:2-2
Regional/ Long	E:3 A:1-3	E:5 A:2-2	E:2 A:1-2	E:4 A:2-3	E:5 A:3-2
Regional/ Medium	E:3 A:1-3	E:5 A:2-2	E:2 A:1-2	E:4 A:2-3	E:5 A:3-2
Regional/ Accidental	E:1 A:1-1	E:1 A:1-1	E:2 A:1-2	E:2 A:1-2	E:4 A:3-2
Local/ Long	E:4 A:2-2	E:5 A:3-3	E:2 A:1-2	E:2 A:1-3	E:5 A:3-2
Local/ Medium	E:4 A:2-2	E:5 A:3-3	E:2 A:1-2	E:2 A:1-3	E:5 A:3-2
Local/ Accidental	E:4 A:3-2	E:5 A:3-1	E:2 A:1-1	E:3 A:2-2	E:4 A:3-2
Extrapolation approximation between victim	E:0.65 A:0.5-0.65		-	E:0.65 A:0.5-0.65	
Interpolation approximation between substance	E:0.8 A:0.65-0.8		-	E:0.8 A:0.65-0.8	
Extrapolation approximation between substance	E:0.65 A:0.5-0.65		-	E:0.65 A:0.5-0.65	
Fitting of experimental conditions	E:0.8 A:0.65-0.8		-	-	-

*E: Score of E_{TD}, A: Scores of Au_{TD} and Av_{TD} (Au_{TD}-Av_{TD})

Table 4-9 Reduction coefficient of accuracy on uncertainty by calculation with assumption in EI (Cal)

Reduction coefficient	(The calculation of EI estimates)
1.0	Exposure amount (Exposure analysis)
0.9	Probability of accidental failure with specific databases (Probabilistic analysis)
0.8	Mid-point of adverse effects (Mid-point impact assessment)
0.65	End-point of adverse effects (End-point impact assessment)
0.50	Aggregation of several adverse effects into an indicator
0.5	Probability of accidental failure without databases (Probabilistic analysis)

Table 4-10 Scoring rule of accuracy value on uncertainty and variability (Au and Av)

Score	(The accuracy of the evaluation utilizing TD and HP is)
3	Accurate enough to be able to make a decision
2	Acceptable with careful interpretation on the meaning of EI
1	Not recommended unless just a trial calculation

The accuracy of evaluation has a non-negligible interaction with the physical exactitude. To heighten the exactitude of the evaluation of complicated adverse effects such as human health by global warming, the assumptions and approximations must be included in the calculation, and result in the increase of model uncertainty. Although data variability is also the factor of reducing accuracy of evaluation, the accuracy can be addressed by a sensitivity analysis with Monte Carlo simulation.

Equation (4-2) shows the calculation of the recommendation level of EI on accuracy (R_Level(A)).

$$R\_Level(A)=\frac{1}{2}\left\{\frac{\left(\sum_{i}^{N_{td}} Au_{TD,i}\cdot\prod_{i}^{N_{a,td}} Assum_{ATD,i}\right)+\left(\sum_{i}^{N_{td}} Au_{HP,i}\cdot\prod_{i}^{N_{a,td}} Assum_{AHP,i}\right)}{\max(A)\cdot\left(N_{td}+N_{hp}\right)}\cdot Cal\right.$$
$$\left.+(1-\alpha)\cdot\frac{\left(\sum_{i}^{N_{td}} Av_{TD,i}\cdot\prod_{i}^{N_{a,td}} Assum_{ATD,i}\right)+\left(\sum_{i}^{N_{td}} Av_{HP,i}\cdot\prod_{i}^{N_{a,td}} Assum_{AHP,i}\right)}{\max(A)\cdot\left(N_{td}+N_{hp}\right)}+\alpha\right\} \tag{4-2}$$

where $Au_{TD,\,i}$: accuracy value of TD_i on uncertainty ($1\leq Au_{TD}\leq 3$, integer), $Au_{HP,\,i}$: accuracy value of HP_i on uncertainty ($1\leq Au_{HP}\leq 3$, integer), $Av_{TD,\,i}$: accuracy value of TD_i on variability ($1\leq Av_{TD}\leq 3$, integer), $Av_{HP,\,i}$: accuracy value of HP_i on variability ($1\leq Av_{HP}\leq 3$, integer), N_{td} and N_{hp}: the number of TD and HP required for an evaluation indicator (integer), $Assum_{ATD,\,i}$ and $Assum_{AHP,\,i}$: the degree of assumption applied in TD_i and HP_i ($0<Assum\leq1$), $N_{a,td}$ and $N_{a,hp}$: the number of assumption (integer) and max(A): the maximum value of physical exactitude (3), α: the enhancement of accuracy on variability by Monte Carlo simulation ($0\leq\alpha\leq1$), Cal: the reduction rate of accuracy on uncertainty by the calculation target ($0<Cal\leq1$).

Table 4-9 shows the reduction coefficient of accuracy on uncertainty by calculation with assumption in EI. Exposure analysis has the highest coefficient, being 1.0, which means there is no increase of uncertainty in exposure analysis. Probabilistic analysis has two different values, being 0.9 and 0.5. This significant gap is due to the existence of databases, which can indicate the probability of possible failure in process. Without database, the quantified value becomes considerably uncertain. Mid- and end-point impact assessments utilized usually in LCA include uncertainty by the defect of accurate model on environmental impacts. The same situation is true in aggregation methods such as Eco-Indicator99 and LIME integration. The scores of Au_{TD} and Av_{TD} are organized in **Table 4-7** and **Table 4-8** on TD and HP, respectively.

Table 4-10 shows the scoring rule of accuracy value on uncertainty and variability. The scores of accuracy of evaluation are organized in **Table 4-7** and **Table 4-8** on the uncertainty and variability originated in TD and HP utilized for EI, respectively. The scoring is based on the relative comparison among each available category of TD and HP.

Practicability/Feasibility

Practicability of evaluation should include data availability, calculation practicability and the understandability of results for making a decision. Among them, data availability is the most critical for evaluation, because the others can be supported by software tools and seminars. Although the implementation of information infrastructure can be a data acquisition for decision-maker, the process foreground data is not included in the database, obviously. Such data should be obtained by decision-maker. The availability of HP may be one of the concerns on the practicability of risk evaluation. In this research, however, the risks are specified on existing HPs accumulated in existing hazard databases as a premise of risk specification. Therefore, the data availability of HP is not considered.

Equation (4-3) shows the recommendation level on practicability (R_Level(P)).

$$R\_Level(P) = \frac{\sum_{i}^{N_{td}} P_{TD,i}}{\max(P) \cdot N_{td}} \quad \textbf{(4-3)}$$

where $P_{TD,i}$: practicability value of TD_i ($1 \leq P_{TD} \leq 5$, integer), N_{td}: the number of TD required for an evaluation indicator (integer), and max(P): the maximum value of practicability (5). **Table 4-11** shows the scoring rule of the practicability of evaluation on the data availability of required TD. The scores of practicability are organized in **Table 4-12**.

Data availability is different for the TDs of own process or other process in life cycles. For own process TD, almost all data can be available for decision-maker, usually. This is not influenced by whether extensive or intensive data. On the other hand, without available databases and estimation models, other process TDs cannot be obtained originally. This situation is considerably true for intensive data. If there is a connection with the engineers at other processes, some of data may be available. In this regard, however, intensive data is still difficult for decision-maker to obtain. The existence of suitable and appropriate databases and estimation models can change all data availability. Such information infrastructure should be accessible for all kinds of decision-makers.

Table 4-11 Scoring rule of practicability of evaluation on data availability of TD

Score	(The practicability of the evaluation utilizing TD is)
5	Very high because of the high availability of TD
4	High because the TD can be available with an effort
3	High with some efforts
2	Low without special efforts
1	Very low
0	Significantly low

Table 4-12 Scores of practicability of evaluation on data availability of TD

	Raw data	Raw data with simple conversion	Raw data by measurement	Raw data with technical conversion	Background data	Estimation
Own process (Extensive data)	P:5	P:5	P:4	P:2	-	P:4(2*)
Own process (Intensive data)	P:5	P:5	P:4	P:2	-	P:4(2*)
Other process (Extensive data)	P:3	P:3	P:1	P:1	P:4(2*)	P:4(2*)
Other process (Intensive data)	P:2	P:2	P:1	P:1	P:4(2*)	P:4(2*)

* The case without any general databases and estimation models

In the procedure of risk specification shown in **Figure 4-3**, the user should judge the risk indices and indicators based on the availability of TD. This means the recommendation level of practicability has less meaning for the recommendation in risk specification than the exactitude and the accuracy scores. The user judges the practicability finally. However, potential practicability should be attributed to each evaluation for the development of novel method for practical application.

4.2.5. Case Study: Local Risk and Global Impact

In order to demonstrate the benefits by risk specification proposed in the previous sub-sessions, local risks and global impacts associated with metal cleaning process are discussed by comparing specified risk indices and indicators by proposed method with the actual evaluation case studies in section 3.3. The following discussions include the role and benefits of RCM in the objectives settings of evaluation and the interpretation of its results, and the difference among plant-specific RA and LCA indicators indicated by the recommendation levels on physical exactitude, accuracy and practicability.

RCM Application in Evaluation

During the procedure of risk specification in **Figure 4-3**, four RCMs are created to compare and recognize the correctness of specified risk indices and indicators, as shown in **Figure 4-6**. The risk specification in this case study is based on the life cycle of cleansing agents shown in **Figure 3-14**. This is the life cycle model to be defined in the first step of risk specification in **Figure 4-3**. For each separated life cycle stage, risk specification is executed. This case study focuses on the cleaning stage in the life cycle in **Figure 3-14**.

Table 4-13 and **Table 4-14** show the mapped HPs and EIs on RCM associated with the existing chemical substances in cleaning stage, where DCM is utilized as cleansing agent. The underlined items in **Table 4-13** and **Table 4-14** mean HPs and EIs applied in the evaluations in sub-sections 3.3.3 and 3.3.4. According to these RCMs, it is visualized that there are many HPs which is not taken into account in evaluations. Especially, some parts of adverse effects on spatial and temporal aspects were not considered at all, such as local/accidental, and local-environmental/medium effects, in spite of the existence of HPs.

At the same time, RCM mapping HPs can visualize the tendencies and causative substances in a life cycle stage. **Table 4-13** indicates a lot of HPs possibly causing local risks. Acute and chronic toxicities of DCM have large contribution to increase the HPs in the category. This can be changed for other types of cleansing agents, for example, alcoholic agent might increase fire/explosion HPs in local/accidental category.

Figure 4-8 organizes the assumptions of $\mathrm{DALY}_{\mathrm{actual}}$ and $\mathrm{DALY}_{\mathrm{marginal}}$. $\mathrm{DALY}_{\mathrm{actual}}$ indicates the neighbors' and workers' health risks. $\mathrm{DALY}_{\mathrm{marginal}}$ is the sum of the DALYs originating from photooxidant creation, air pollution in urban area, release of human toxic chemicals, and global warming. In the calculation of $\mathrm{DALY}_{\mathrm{actual}}$, the medium-term and long-term exposures were regarded as the same dimension and aggregated. It is assumed that the DALYs originating from different environmental impacts can be summed up, even though the spatial and temporal aspects of them would be different. Such assumption of evaluation results tends to be hidden in the graph showing quantitative results such as **Figure 3-12**, **Figure 3-13**, and **Figure 3-15**. RCM mapping the evaluated indicators could visualize the hidden assumption of EI, which should also be taken into account in the interpretation for risk-based decision-making.

Ranking of Available Evaluation Indicators

Based on the method of recommendation described in sub-section 4.2.4, some existing EIs are ranked for risk specification. HPs and TDs dominate the ranking of EIs requiring them. The following discussion includes the risk specification of own process evaluation, i.e., cleaning stage, and other process evaluation for decision-maker.

Local Risks in Own Process Evaluation

Decision-maker must identify local risks in own process concretely and can collect required TD in detail. This case study focuses on workers' health risks as local risk in a cleaning process utilizing DCM as cleansing agent. As available EIs combined with TD and HP, four types should be taken into account: MOE, $\mathrm{DALY}_{\mathrm{actual}}$, which are calculated by intensive foreground data, $\mathrm{DALY}_{\mathrm{actual}}$ calculated by intensive background data, and $\mathrm{DALY}_{\mathrm{marginal}}$ calculated by extensive background data with the impact factor estimated by general model. For the comparison of EIs based on HPs having different features on the experimental conditions, this case study includes the MOE of TCE in cleaning process. **Figure 4-9**-(a) shows the recommendation chart of targeted EIs on local risks in own process. Note that the MOE (TCE) is the result to analyze the influence of the experimental condition of HP. It should not be compared with the other EIs for DCM.

If the ranking of EIs is based on the recommendation level of physical exactitudes, the highest recommended EIs are MOE (DCM) and $DALY_{actual}$ by intensive foreground data. They have same value of R_Level(E) followed by $DALY_{actual}$ by intensive background data. In this regard, however, for on-site engineers in cleaning process, intensive background data for $DALY_{actual}$, that is the workplace concentration, is lower available than foreground one, because they have the measured value obtained by the regulated measurements on OPOSP. This is because the R_Level(P) is lower than those of other EIs. Based on the physical exactitude, $DALY_{marginal}$ is the lowest recommended EI. The reason why there is a gap between R_Level(E) of $DALY_{actual}$ and $DALY_{marginal}$ should be that $DALY_{marginal}$ ignores the background concentration in general environment and sets threshold of non-carcinogenic effects as zero. In the proposed recommendation approach, the R_Level(E) of $DALY_{marginal}$ is lowered by the use of extensive data for local risks and general model prediction. Although the meanings of $DALY_{actual}$ and $DALY_{marginal}$ are different, the proposed method can reflect the weak point of $DALY_{marginal}$, accordingly.

In **Figure 4-9**-(a), the MOE(TCE) has a great R_Level(E). This is because HP is available without approximations for the calculation of local human health risks of TCE. The quality of available data leads to the difference of physical exactitudes of the same EI, i.e., MOE of DCM and TCE.

Figure 4-10 demonstrates an example of risk specification procedure for local human health risks. This procedure is based on the R_Level(E) of EIs, especially DALY, for local risks in cleaning process utilizing DCM. According to **Figure 4-9**-(a), the order of recommendation is $DALY_{actual}$ by intensive foreground data, $DALY_{actual}$ by intensive background data, and $DALY_{marginal}$ by extensive background data. **Figure 4-10** demonstrates that $DALY_{marginal}$ is decided as the final decision for specified EI through the consideration of other EI with higher recommendation than $DALY_{marginal}$. Final decision should be always based on the actual situation of decision-maker, especially on the data availability. Therefore, risk specification accordingly becomes strongly dependent on it. This is highly practicable, but not scientifically desirable mechanism. The development of supporting information system is strongly needed for an appropriate risk specification.

Table 4-13 Hazardous properties applied by the evaluated risk indices in the case study

	LS: Cleaning	Temporal aspects					
		Accidental occurrence in use (incl. short-term occurrence after emission)		Medium-term occurrence after emission		Long-term occurrence after emission	
Spatial aspects	Local						
	- workplace	LEL/UEL(75092,8008206) A-I-T(75092,8008206) FP(8008206) STEL(75092,7446095,10102440,124389)	R45-36/38-52/53-67(75092) R65(8008206) R23(7446095) R26(10102440) R34(7446095,10102440) EU:T(75092,7446095) EU:Xn(8008206) EU:T+(10102440)	TWA(75092,7446095,10102440,124389), LD50/LC50(75092,7446095,10102440), NOAEL/NOAEC(75092,7446095,10102440), LOAEL/LOAEC(75092,7446095,10102440)	R36/38-67(75092) R65(8008206) R23(7446095) R26(10102440) R34(7446095,10102440)	TWA(75092,7446095,10102440,124389) NOAEL/NOAEC(75092,7446095,10102440) LOAEL/LOAEC(75092,7446095,10102440)	R45-36/38-67(75092) R65(8008206) R23(7446095) R26(10102440) R34(7446095,10102440)
	- neighborhood	LEL/UEL(75092,8008206) A-I-T(75092,8008206) FP(8008206)		LD50/LC50(75092,7446095,10102440) NOAEL/NOAEC(75092,7446095,10102440)	LOAEL/LOAEC(75092,7446095,10102440)	NOAEL/NOAEC(75092,7446095,10102440) LOAEL/LOAEC(75092,7446095,10102440)	
	- environment	LC50/EC50(75092) NOEC(75092) LOEC(75092)		LC50/EC50(75092) NOEC(75092) LOEC(75092)	R52/53(75092)	NOEC(75092) LOEC(75092)	R52/53(75092)
	Regional						
	- environment			OCEF(75092,8008206), AETP;a,w,s.(75092), TETP;a,w,s.(75092), NPP-OCEF(75092,8008206)		DAP(7446095,10102440), AETP;a,w,s.(75092), TETP;a,w,s.(75092),	EINES-ETP;a,w,s.(75092), NPP-AcidP(7446095,10102440)
	- population			DALY-OCEF(75092,8008206) DALY-AirPollut.(7446095,10102440)		HTP_canser;a,w,s.(75092), HTP_chronic_dis.;a,w,s.(75092),	DALY-HTP;a,w,s.(75092)
	- society			Social resource-OCEF(75092,8008206)		Social resource-AcidP(7446095,10102440),	
	Global						
	- environment			Land_use		GWP;20,100,500.(75092,124389), NPP(Land_use,natural resorce(8008206)),	EINES-(Land_use, natural resorce(8008206))
	- population					DALY-GWP(75092,124389)	
	- society					Social resorece-GWP(124389) Social resorce-natural resorce(8008206)	1/R-natural resorce(8008206) Social resorce-waste, Waste volume

CAS#	Chemical
75092	Dichloromethane
8008206	Kerosene
7446095	Sulfur dioxide
10102440	Nitrogen dioxide

Table 4-14 Evaluation indicators applied in the case study

LS: Cleaning

Spatial aspects		Temporal aspects					
		Accidental occurrence in use (incl. short-term occurrence after emission)		Medium-term occurrence after emission		Long-term occurrence after emission	
	Local						
	- workplace	HAZOP(75092,8008206) FTA(75092,8008206) HQ(75092,7446095,10102440,124389)	Risk(75092,7446095,10102440,124389) MOE(75092,7446095,10102440,124389)	MOE(75092,7446095,10102440) DALY_actual(75092,7446095,10102440)	HQ(75092,7446095,10102440) Risk(75092,7446095,10102440)	MOE(75092,7446095,10102440) DALY_actual(75092,7446095,10102440)	HQ(75092,7446095,10102440) Risk(75092,7446095,10102440)
	- neighborhood	HAZOP(75092,8008206) FTA(75092,8008206)		MOE(75092,7446095,10102440) DALY_actual(75092,7446095,10102440)	HQ(75092,7446095,10102440) Risk(75092,7446095,10102440)	MOE(75092,7446095,10102440) DALY_actual(75092,7446095,10102440)	HQ(75092,7446095,10102440) Risk(75092,7446095,10102440)
	- environment	HQ(75092) Risk(75092) MOE(75092)		HQ(75092) Risk(75092) MOE(75092)		HQ(75092) Risk(75092) MOE(75092)	
	Regional						
	- environment			OCEF(75092,8008206), AETP;a,w,s.(75092), TETP;a,w,s.(75092), NPP-OCEF(75092,8008206)		DAP(7446095,10102440), AETP;a,w,s.(75092), TETP;a,w,s.(75092),	EINES-ETP;a,w,s.(75092), NPP-AcidP(7446095,10102440)
	- population			DALY_marginal-OCEF(75092,8008206) DALY_marginal-AirPollut.(7446095,10102440)		HTP_canser;a,w,s.(75092), HTP_chronic_dis.;a,w,s.(75092),	DALY_marginal-HTP;a,w,s.(75092)
	- society			Social resource-OCEF(75092,8008206)		Social resorce-AcidP(7446095,10102440),	
	Global						
	- environment			Land_use		GWP;20,100,500.(75092,124389), NPP(Land_use,natural resorce(8008206)),	EINES-(Land_use, natural resorce(8008206))
	- population					DALY_marginal-GWP(75092,124389)	
	- society					Social resorece-GWP(124389) Social resorce-natural resorce(8008206)	1/R-natural resorce(8008206) Social resorce-waste, Waste volume

CAS#	Chemical
75092	Dichloromethane
8008206	Kerosene
7446095	Sulfur dioxide
10102440	Nitrogen dioxide

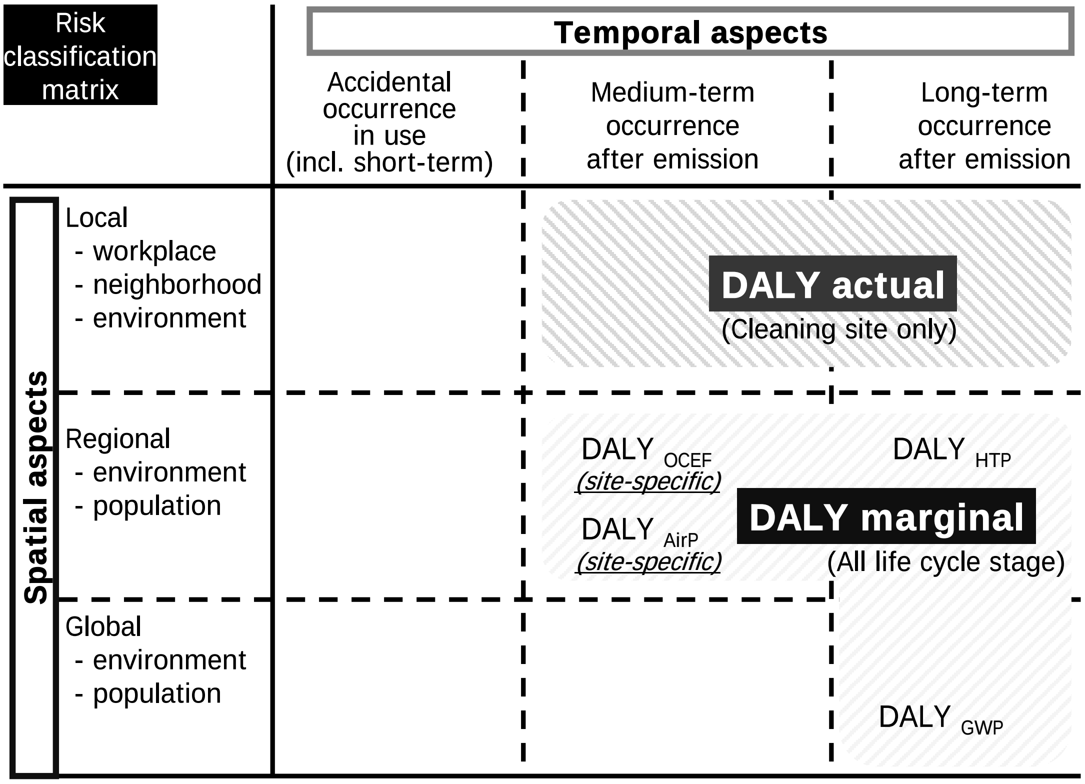


Figure 4-8 RCM for identifying the assumptions of $\text{DALY}_{\text{actual}}$ and $\text{DALY}_{\text{marginal}}$

Evaluation of Site-specific Impacts

Regionalization of evaluation has been necessitated for some environmental impacts (Haes 2002), which cause adverse effects based on geographical differences and features. Existing LCIA methods take into account such regionalization to evaluate acidification, photochemical oxidant creation, and air pollution in urban area. Corresponding to the LCIA methods, LCI should collect the site-specific inventory data. However, such regionalized database is sometimes non-available and site-generic impact assessment has been performed.

Figure 4-9-(b) shows the comparison of site-generic and specific evaluation for the impacts to be regionalized. Because both evaluations utilize the same TD, the R_Level(P) indicates a same value. The R_Level(E) of site-generic EI is lower than that of site-specific one. This owes to the assumption of approximating the region-specific data to generic data. This approximation is also the reason to reduce the value of R_Level(A) of site-generic EI.

According to the results shown in **Figure 4-9**-(b), the site-specific EI should be utilized for regionalized environmental impacts. The possibility of making such evaluation impossible is the deficiency of databases storing geographical information of TD. **Figure 4-9**-(b) shows the R_Levels of the evaluation for the life cycle stage including own process of decision-maker. For other processes, the R_Level(P) might be lower than that of **Figure 4-9**-(b), being 0.8 with database and 0.4 without database.

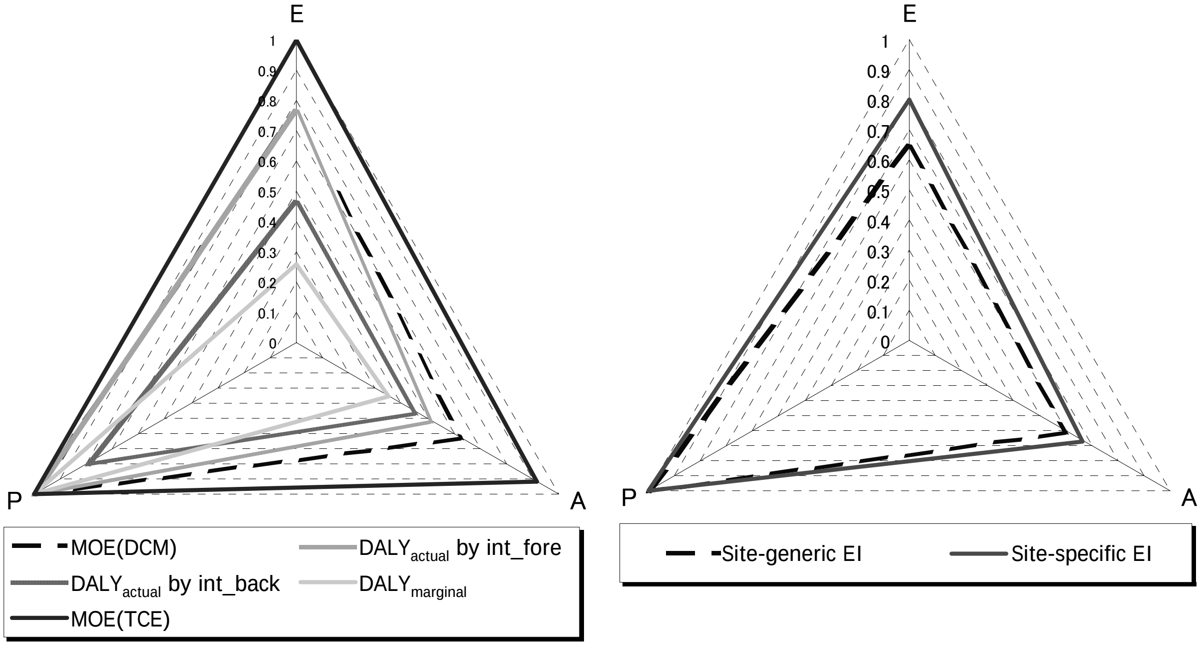
DALYs Attributable to Various Impacts

In the most of LCIA methods, DALY has been selected as the indicator for human health impacts attributable to all environmental impact. Because the category end-points of several impacts can be human health and there are different types of adverse effects on it, DALY has become a great indicator in LCIA due to the generic applicability. Although practitioners have applied DALY into their evaluations, the detail consideration has not achieved enough level to distinguish the meanings of DALYs in detail.

Figure 4-9-(c) shows the R_Level chart of DALYs originating from global warming, site-specific environmental impacts, or photooxidant creation, and all types of impact categories, one the end-points of which is human health. The results clarify the difference of R_Levels of each DALY dependently on the characteristics of the environmental impact and the assumptions of each EI. The summation of them definitely reduce the complication of evaluation results. In **Figure 4-9**-(c), however, the R_Level of the total DALYs of various environmental impacts is not so high on the physical exactitude. For the sake of comparing process or system on environmental impacts, LCIA methods have tries to aggregate impacts into an indicator. Comparison can lead to the simplification of making decision, however, it is hardly possible to make the discussion for judging the enough improvement of process toward sustainability with the careful consideration of adverse effects.

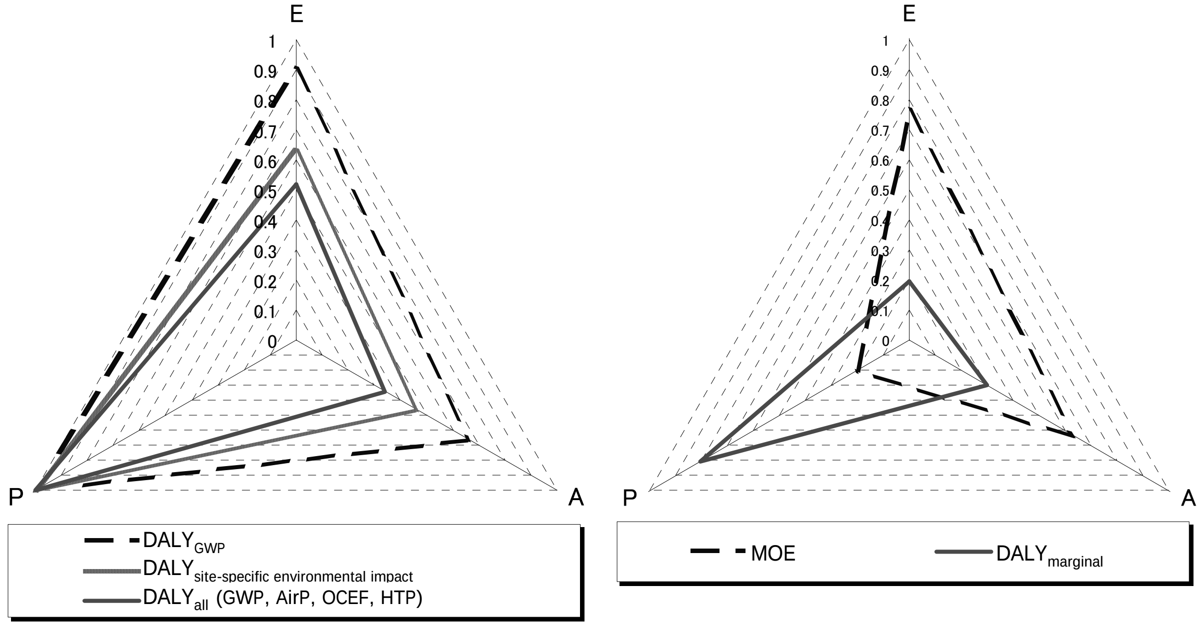
Local Risks in Other Process Evaluation

For other process evaluation, a decision-maker might have limitation of data availability at this present. Complete database storing intensive foreground data of each process in a life cycle would be needed to execute the same level evaluation as own process. **Figure 4-9**-(d) shows the R_Level of MOE and $\text{DALY}_{\text{marginal}}$ for the evaluation of other process with ordinary information infrastructure. The results indicate a trade-off relationship among the R_Levels. MOE has larger R_Level(E) than $\text{DALY}_{\text{marginal}}$ due to the several assumptions for calculating DALY from extensive background data. This also results in the decrease of the R_Level(A) of $\text{DALY}_{\text{marginal}}$. R_Level(P) has different tendency from the other R_Levels. Data requirement of $\text{DALY}_{\text{marginal}}$ is extensive background data, decision-maker can collect easy by existing databases. While the practicability of $\text{DALY}_{\text{marginal}}$ is high, that of MOE is low, because of the requirement of intensive data for calculating it.



(a) Local risks in own process
(Workers' health)

(b) Site-specificity of EIs



(c) DALYs originated
in various environmental impacts

(d) Local risks in other process
(Workers' health)

Figure 4-9 Recommendation level charts on
physical exactitude (E), Accuracy (A), and Practicability (P)

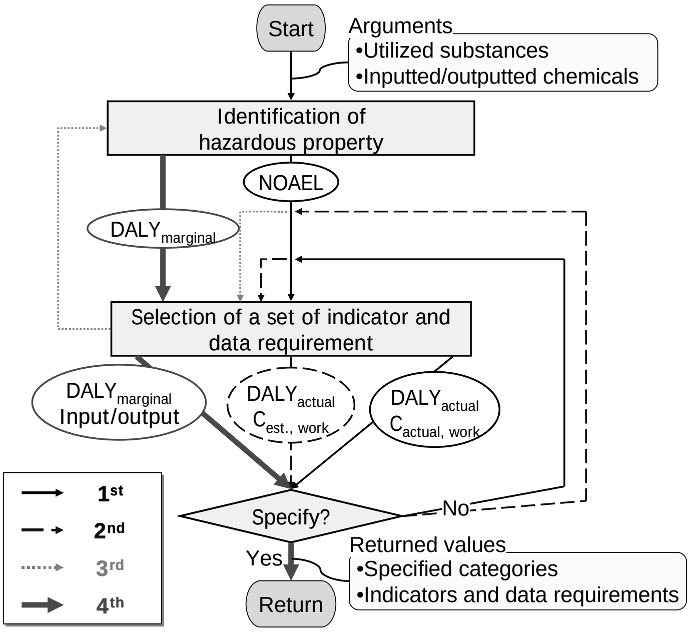


Figure 4-10 Example of Risk Specification of Local Human Health Risks

The increase of attainable EIs can be regarded as to depend on the data availability. To execute an evaluation with high physical exactitude, data acquisition should be stable for various process stages.

4.2.6. Conclusion

This section presents risk specification method to identify, recognize and specify appropriate risk indices and indicators, which associates the knowledge on risk evaluation methodologies. In order to make the selection of them based on scientifically- and practically-valid logic, this section proposes a strong cooperation between a transparent procedure of screening possible risk indices and indicators and an information system on hazardous properties of chemicals and available evaluation indicators. The procedure of risk specification is quite simple with clear logic toward the completeness of consideration of risk indices and indicators. It can be rewritable as a process flow chart in computer processing.

For activating the procedure of risk specification, relational data storage should be able to structure and accumulate information on risk indices and indicators. For establishing a distinguishingly effective structure of risk information, risk classification matrix is developed and it could visualize the difference among existing hazardous properties of chemicals and evaluation indicators on their spatial and temporal aspects. Such mapping can be useful information to identify the possible risk in a process utilizing chemical substance. Along with the procedure of risk specification, existing case study of evaluating metal cleaning process was traced to demonstrate the benefits of risk classification matrix. The visualization of spatial and temporal aspects can indicate the correct meaning of evaluation indicators in detail, but easier than simple description by documents. It can also show the hidden assumption of evaluation indicators, which cannot be revealed during ordinary evaluation. Risk interpretation should take into account such revealed assumption of evaluation indicators.

At the screening of risk indices and indicators, decision-maker should specify possibly better ones on scientific meaning. This section also discussed the recommendation method for adequate evaluation. The recommendation level was divided into physical exactitude, accuracy, and practicability. The scoring rules of them were decided to be able to compare existing evaluation indicators. Actual analyses of recommendation of existing evaluation indicators were performed on local risks in own process and other process, regionalization of environmental impacts, and the aggregation of human health impacts originating from different impacts. The results could demonstrate the benefits of proposed recommendation level, which distinguish and rank available indicators.

The proposed risk specification mechanism has the possibility to gather and integrate the decentrally-generated knowledge on risk evaluation. The proposed algorithm, structure of knowledge, or risk classification matrix, and recommendation analysis are the 1st draft of challenge to integrate various risk evaluation including EHS categories and LCA indicators toward decision-making for sustainability.

With regard to the practicability of such risk specification described as a logical algorithm, additionally, knowledge on scientific assessments is not enough for actual evaluators, e.g., on-site engineers and policy makers, to consider them comprehensively. Information infrastructure can be one of the strong tools to support actual evaluators to go through the steps of risk specification. Especially, database system is applicable to organize the systematized knowledge on risk evaluation. The software algorithmic discussion on risk specification is described in Chapter 5.

4.3. Risk-Based Generation of Alternative Candidates

4.3.1. Introduction

Alternative generation is one of the most important activities in risk-based decision making. There can be a huge range of available alternatives possibly reducing risks. It is not feasible to evaluate and consider all possible alternatives. Furthermore, innovative alternatives might exist in actual engineering fields. However, the mechanism of innovation from existing knowledge on process is quite complicated and not simple to transcribe into algorithm logically.

In risk-based generation of alternative candidates, evaluation results can be available and should become one of the rationales of alternative generation. In ordinary process design, productivity, economical profit, and safety in manufacturing have been the objectives, and thus a plenty of heuristics on design for such objective functions has been established and applied in various field of engineering. Engineers have empirical and intuitive skill of seeking better design of alternatives. When it comes to design for environment and risk reduction, not enough “intuition” has been available because of little practical training in site.

In order to activate such untried alternative generation for on-site engineers, novel linkage of knowledge on risk and process should be developed and practicable for them as an activity in a business model. Such business model should be able to consider decidable parameters, which is dependent on decision maker: for on-site engineers in industrial process, process parameters might be decidable, and for policy makers, regulations can be decidable, some of which will make changes in system parameters partly dominating life cycle model. These parameters compose and achieve required process function, and incidentally lead to risk. This section proposes the association of fundamental knowledge for risk-based generation of alternative candidate. The main pillar of proposed association is linkages among process functions, local risk, global impact and decidable parameters. Proposed association indicates knowledge receptacles and the method to storing knowledge on them. Note that a case study is performed on the process modeling of cleaning process, which is mentioned in section 4.5.

4.3.2. Alternative Generation Strategy with Structured Knowledge

Procedure of Alternative Generation

Figure 4-11 shows the procedure of alternative generation based on structured knowledge, which includes heuristics of industries on process, understandings of LCA and RA, and process model to be developed and available on site. This procedure needs the extended association of the knowledge on EvM and AGM. Actual alternative generation can utilize plant-specific information, especially in retrofitting design, the evaluation results of process in use should be referred as the facts in targeted process. Based on the knowledge of LCA and RA, the process data affecting evaluation results can be specified. Process model can represent process parameters linking to the data causing risk. Heuristics characterize the role of the process parameters in process functions.

Contribution analysis is one of the method to specify the dominant factors. In ordinary LCA, contribution analysis is performed on the life cycle stages in system boundary. For alternative generation at the specific viewpoint of on-site engineers, such contributions of life cycle stages cannot be useful information. In this time, the contributions of risk factors linked to process parameters are analyzed.

Based on such contributions, the priority of improving the factors can be identified. At this time, if not-decidable parameters have large contribution to evaluation results, such information should be transferred to the decision maker having the right to decide them. For the decidable parameters, effective alternative generation is fulfilled based on the heuristics and process model. The performance of AGM depends on the process model connecting process parameters, measured data, and evaluation results. For establishing this model, the linkage among process, functions and risks should be developed to clarify the factors such as process/system parameters, constraints, and physical phenomena. The important requirement of process model is to be able to generate alternatives, which can affect the process data and be simulated.

Decision Table

After contribution analysis on risk factors, alternative technologies possibly effective for the reduction in evaluated risk are generated. For the automation of alternative generation, an algorithm is developed with decision tables enabling the implementation of knowledge on physical phenomena in process into practice. **Figure 4-12** show the flowchart utilizing decision tables, whish are defined as **Figure 4-13**. If the correspondences of decision conditions are confirmed between condition vector of process in use (**Figure 4-13**-(a)) and the columns in decision tables (**Figure 4-13**-(b)), the alternative candidates can be applicable for the risk reduction. The decision tables are developed for each risk factor, and the candidates included in them are the improvement of process parameters attributable to the physical phenomena causing risk. In each decision alternative, a physical phenomenon or relation is addressed and the conditions with value "-" mean that they have no relation with the addressed phenomenon. The flowchart shown in **Figure 4-12** can represent such alternative generation based on decision tables. Specified candidates are ordered by the number of recommendation in the narrowing of alternatives by decision tables.

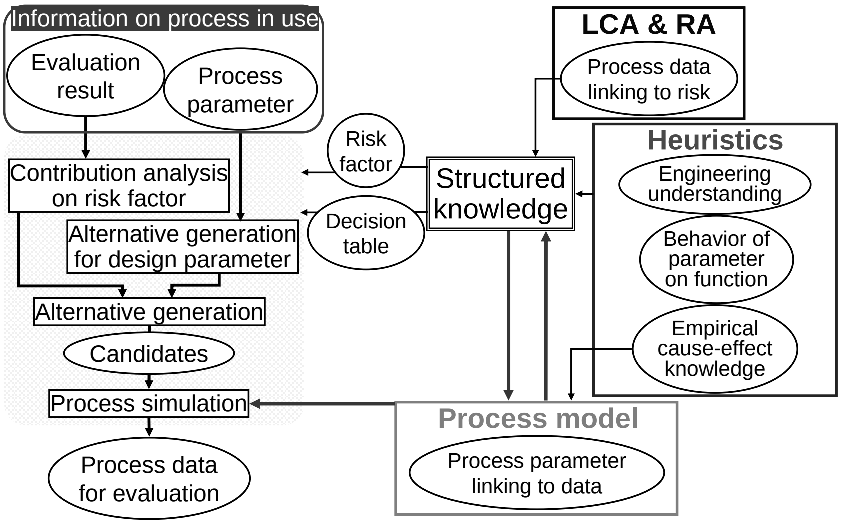


Figure 4-11 Procedure of alternative generation based on structured knowledge

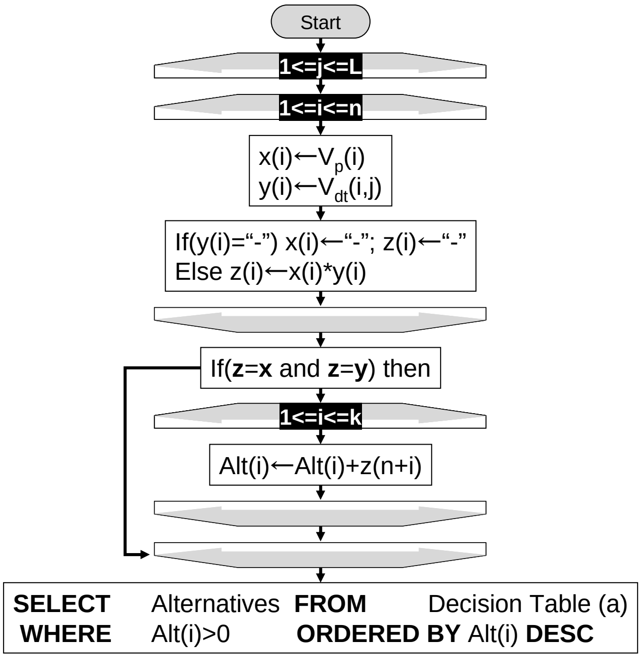
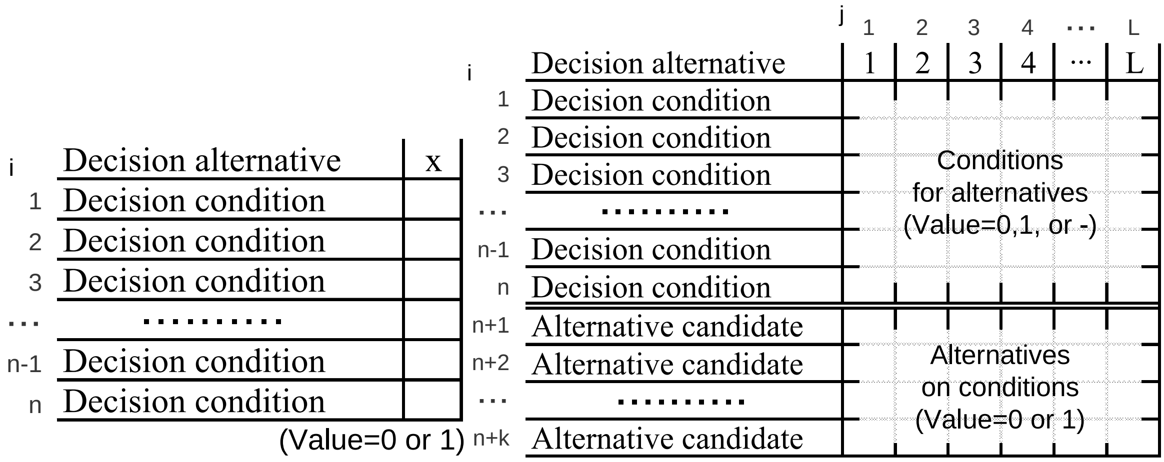


Figure 4-12 Flowchart of alternative generation based on decision tables



(a) Condition vector of process in use (b) Decision table

Figure 4-13 Condition vector and Decision table for alternative generation

4.3.3. Association of Knowledge on Physical Cause-Effect Chain

Linkage Creation between Decidable Parameters and Function/Risk

Linkage creation between decidable parameter and function/risk means the establishment of cause-effect chain of function and risk. In this establishment, systematic definition and storage of knowledge are essential as discussed in section 2.1. The knowledge on process and function/risk should be segregated each other.

Decidable and Non-decidable Parameters along with Decidable Range

For decision makers, there is a limitation of decidable parameters, which they can change by their own power of decision. **Figure 4-14** shows the decidable range originating from the viewpoint of decision maker. This figure is based on a typical life cycle model where a life cycle stage can be hierarchically decomposed into plants (sites), processes, and devices. Each component has several parameters such as device, which is the shape, size, or material of installed devices, and operation, which is the information on the operation by workers or settings of devices. With regard to local risks, temperature, the location of devices or the airflow in workplace should be regarded as environment parameters. These parameters exist in all processes in all plants of all life cycle stages. A decision maker can change each existing parameter, even though some regards the parameters, other does not. Parameters unconsciously defined by a decision maker can make a significant influence on function/risk related with and occurred around other decision maker. Cause-effect relationships among parameters and function/risk must be a logical understanding that is inevitable for a risk-based generation of alternative candidates.

Theoretical and Empirical Knowledge for Risk-based Design

The categories of empirical knowledge on alternative generation having been developed on site can be mainly divided into process characteristic, and so-what relation by actions, or cause-effect relationship with imprecise probabilities of them. Such knowledge can be applicable to establish the relationship between process and function/risk in three patterns shown in **Figure 2-6** (a, b, c). Theoretical knowledge on alternative generation should be collected or developed by existing researches, additional experiments, analyses, and simulation. In this time, such collection and development should be able to link existing empirical knowledge. The linkage should meet the necessary and sufficient conditions to describe the rationales of empirical knowledge for risk-based alternative generation.

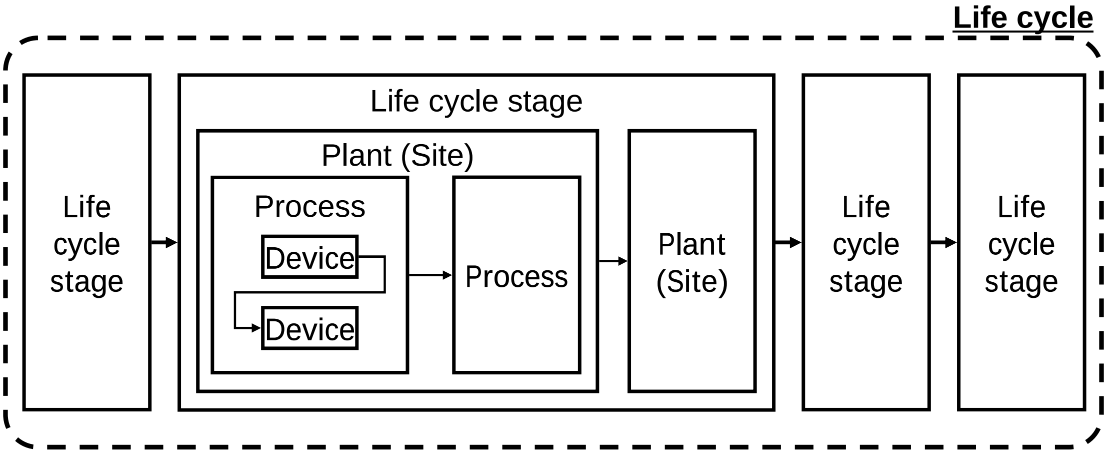


Figure 4-14 Decidable range originating from the viewpoint of decision makers

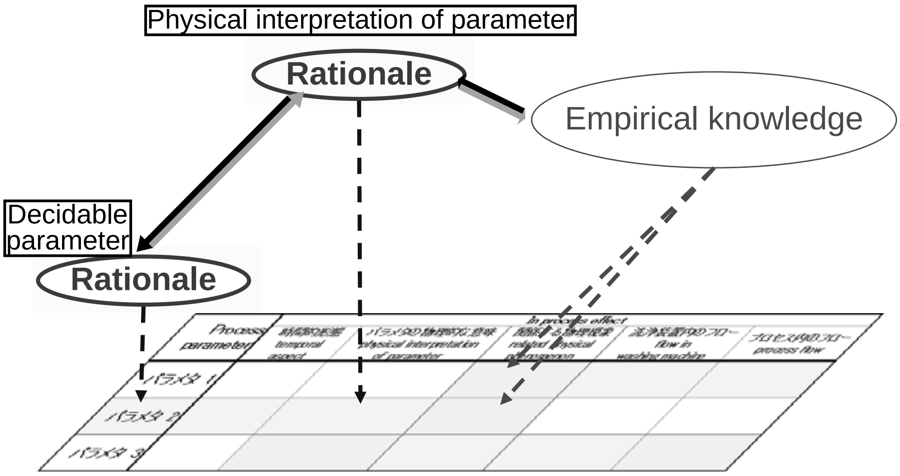


Figure 4-15 Logical connection on coherent semantic unit of physical phenomenon linking cause-effect between decidable parameter and function/risk

Coherent Semantic Unit on Physical Phenomenon

Storage of knowledge linking decidable parameter and function/risk has the dominant influence on the effectiveness, accuracy and practicability of alternative generation. All decidable parameters, which are process and system parameters, can be related with physical phenomena, finally leading to the factors realizing function and causing risk. Therefore, coherent semantic unit on physical phenomenon can segregate and store knowledge on alternative generation. Based on the knowledge stored in such unit, physical connection between decidable parameters and function/risk can be traced with physically logical unit of interpretation as shown in **Figure 4-15**. In this figure, two empirical knowledge is connected each other through decidable parameters and rationale categories, which is physical interpretation of parameter. This means that it was defined as the semantic unit connecting decidable parameter with empirical knowledge. Effective definition of semantic unit is essential for alternative generation. It is discussed in the next sub-sections.

Qualitative Process/System Modeling along with Decidable Range

Establishment of linkage between decidable parameters and function/risk can be a qualitative process/system modeling, including the consideration of non-decidable parameters' linkage. This modeling can reveal the physical connection between each component existing in a process/system. Although it does not mean the development of mathematical modeling, qualitative modeling must become an important foundation for quantitative modelings required for process/system simulation. Semi-quantitative modeling is also based on this modeling. An effective and elaborate linkage can be an essence of actualizing risk-based generation of alternative candidates.

4.3.4. Physical Linkage in Industrial Process

In an industrial process, several parameters on device and operation exist and connect complicatedly with process functions and risks, simultaneously. **Figure 4-16** shows the overview of semantic units among process/system parameters, process system functions, and chemical risks, the explanation of which are organized in **Table 4-15** and **Table 4-16**. A parameter may connect with functions and risks. In such situation, the parameter has a possibility to make a trade-off relationship between them. Even if there is no relation each other, the causative physical phenomenon may be connected with multiple process parameters. The advantage of storing such knowledge is dependent on the execution of developing semantic units. Function and risk sides of linkage are indicated below.

Function-Process Linkage Model

The relationship composes two different functions: base and sub functions. Base functions are attributed to devices and operations in terms of physicochemical and mechanical factors. This function can be a unit function of the parameter inside of a device. Sub-function means the function of device in a process. This function might be achieved by several unit functions actualized by parameters. By integrating each function of devices installed in a process, process system function is actualized and worked in a system, or a life cycle.

Risk-Process Linkage Model

In Process Effect

This effect originates from the process system parameters and happens inside of a process. This unit can be divided into five sub-units: temporal aspect of effect, physical interpretation of parameter, related physical phenomenon, physical flow inside a device, and physical flow outside a device. These sub-units become the foundation of the sufficient understanding of physical linkage, and at the same time, the quantification of model. Additionally, this semantic unit is the minimum one with regard to the relationship between parameters and risks. Sub-units were set so as to be understandable unit for on-site engineers in order to retrieve heuristics established by them. In this meaning, this unit, implemented originally for alternative generation, might become a central unit to associate empirical and theoretical knowledge.

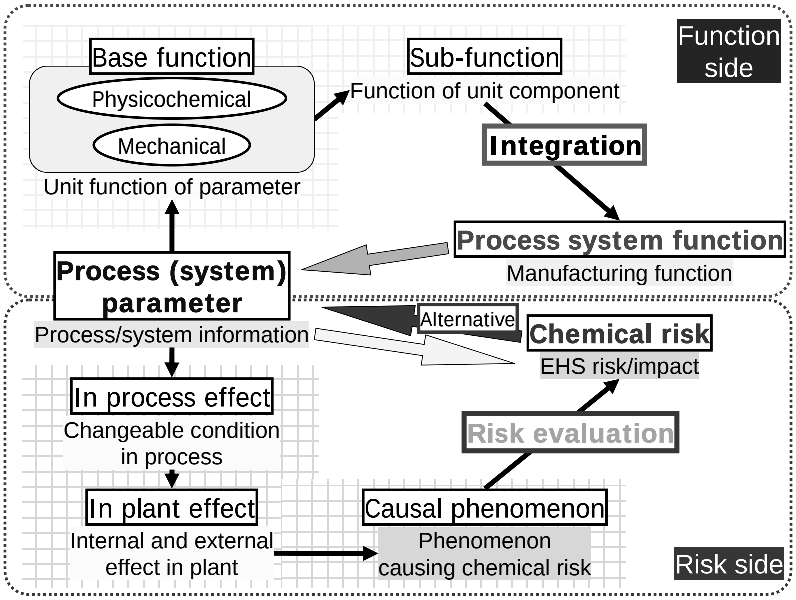


Figure 4-16 Process/system parameter and its relationship between process system function and chemical risk

Table 4-15 Semantic units of process system function-process parameter linkage

Semantic Unit	Explanation
Process/system parameter	Parameters defining processes in industry or systems composing a life cycle
Base function	Unit function achieved by the decidable parameter in a device
Physicochemical	Function actualized by physicochemical ability of the parameter
Mechanical	Function actualized by mechanical ability of the parameter
Sub-function	Function of a device in a process
Process system function	Function of a process in life cycle

Table 4-16 Semantic units of chemical risk-process parameter linkage

Semantic Unit	Explanation
Process/system parameter	Parameters defining processes in industry or systems composing a life cycle
In process effect	Effects happened in a process, including devices
Temporal aspect of effect	Temporal dimension of in process effect related with steady or dynamic state
Physical interpretation of parameter	Physical meaning of the parameter on the viewpoint of physical phenomenon that can be defined in theoretical knowledge
Related physical phenomenon	Physical phenomenon that is taken place in a device and related with multiple process parameters
Physical flow inside a device	Physical flow occurred in a device by the physical phenomenon including mass and heat fluxes
Physical flow outside a device	Physical flow occurred by the flow inside a device, which is out of a device
In plant effect	In plant effect happened in or between plants occurred by the in process effect, which includes flows between processes and plants
Causal phenomenon	Causal phenomenon directly causing chemical risk, which is the result of the in plant effect
Chemical risk	Chemical risks caused by the causal phenomenon.

In Plant Effect

In process effect causes some physical flows and makes changes on intensive parameters. Such changes are regarded as in plant effect, which can stimulate causal phenomenon of chemical risks. In plant effect can be also the target of qualitative and quantitative modelings, because of its requirement for risk evaluations. In this time, the modeling should take into account the plant-specific conditions as well as process conditions: for example, air exchange rate, which is dependent on room ventilation systems etc, and ambient surroundings of sites.

Causal Phenomenon

Causal phenomenon of risks can be recognized several types of causes: for example, inhalational, dermal, and oral exposures to chemicals, ignition, emission into the environment, leak of chemicals, etc. Some of them are steadily happened and others are accidental. Because all plausible scenarios should be taken into account for sufficient risk evaluations, scenario development has a crucial role in risk-based alternative generation. This kind of scenario development includes one as alternative generation and uncertainty analysis.

4.3.5. Summarization

This section presents a procedure of alternative generation associating the knowledge on theoretical analyses on process, heuristics on process behaviors, and process evaluation. In the algorithm of generating alternative candidates from process conditions, decision tables are proposed to associate and store the knowledge on physical phenomena in process, heuristics on process design, and empirically formalized process behaviors. At the same time, the contribution analysis of evaluation results of process in use is applied for prioritizing the risk factors to be improved.

Such combined alternative generation needs the extended association of the knowledge on process evaluation and alternative generation. For example, the improvement of process parameters in alternatives should be able to affect the evaluation results. This means that the process model incorporated into AGM must take into account the process data required for evaluation.

For the fundamental knowledge of AGM, a qualitative process model was proposed by considering semantic units connecting process parameters and function/risk. This model can reveal the physicochemical and mechanical relationship between process system parameters and function/risk. Based on the revealed logical relationship, alternative parameters can be assumed to reduce targeted risks with keeping enough process system function. Development of proposed linkage models and assessment methodology enables the recognitions of each risk reduction by alternatives. Toward such integration, quantitative process modeling should be able to consider the process system parameters in linkage models. Process system parameters are divided into device, operation and environment to address and evaluate chemical risks. Effective alternative generation and evaluation needs physical and mathematical models of targeted process systems.

4.4. Process Modeling for Assessments of Local Risk and Global Impact

4.4.1. Introduction

Because alternative processes are not existence actually, the process data must be estimated during process design. In chemical process design, mathematical models were established on the basis of a huge amount of process analyses, experiments, and modelings on the processes having the similar aspects for systematic process design (Biegler 1997; Duncan and Reimer 1998). Such models enable the process simulation before constructing plants, and screening of alternatives with gradual experiments by pilot and mini plants.

Systematic process design has a big obstacle of uncertainties in simulation and evaluation results due to the limitation of information at each design phase (Sugiyama 2007). Even for mass and heat balances, the estimation results by process models have somewhat uncertainty. Obviously, the estimation of data required for LCA and RA is challenging. However, it is strongly needed for risk-based decision making.

This section presents the process modeling method for estimating data required for LCA and RA. This modeling approach is basically applicable for retrofitting process design at this present. If databases of process data under specific plant conditions are maintained, this approach can be possible even for grass-root process design.

4.4.2. Model Requirement and Approach

Figure 4-17 shows the available data along process design phases between existing and alternative candidate processes. At the phase of alternative generation, the information on the process data is limited and far from the amount of performing LCA and RA. Process models have the role of filling the gaps of knowledge on process data. If there is no special method of process modeling, considerably strong process models must be developed to fill the gaps of knowledge between the knowledge levels A, shown in **Figure 4-17**, and existing process. DBs on previous cases similar to the existing one can be support information for the filling of gaps as level B shown in **Figure 4-17**. Additionally, the extrapolation from actual data of existing process has great potential for the estimation of process data as level C shown in **Figure 4-17**.

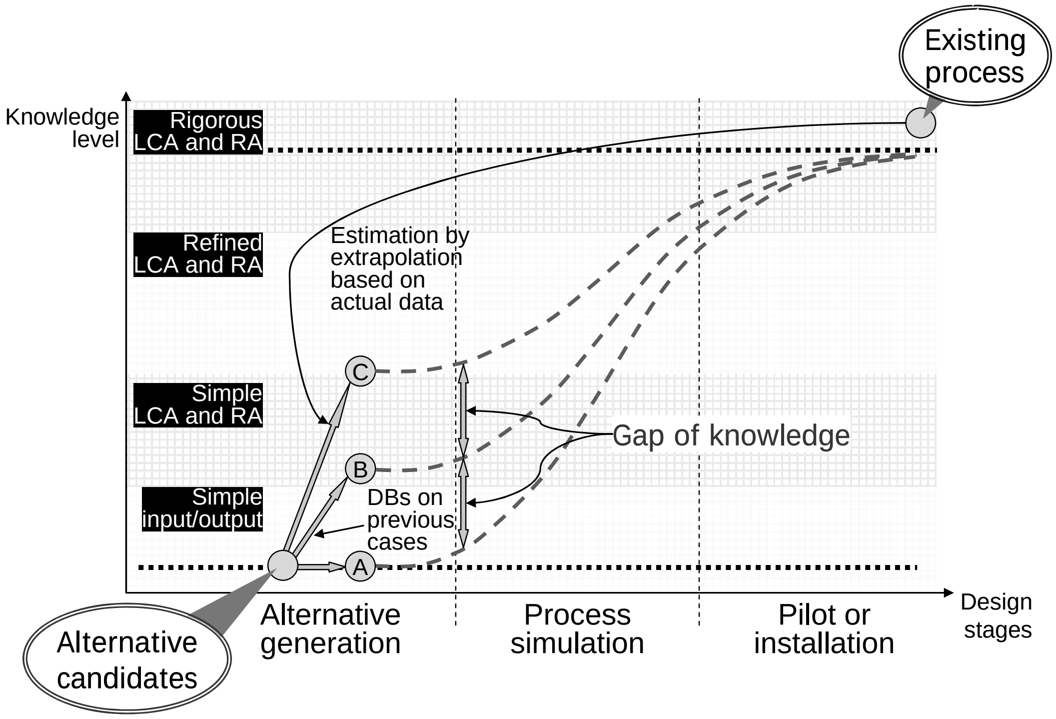


Figure 4-17 Available data along process design stages between existing and alternative candidate processes

4.4.3. Association of Knowledge on Process Behavior

Simple mass and heat balances are not sufficient for the appropriate process modeling for risk-based decision making. To consider the effect of alternation of process parameters enough to estimate not only extensive, but also intensive aspects of process, physical understandings must be available on each components of a process. At the same time, some physical linkage between process parameters and data must be represented as mathematical models.

Figure 4-18 schematically shows the applicable modeling methods. Basically, modeling is started from evidences. Process models are proposed through reasoning and associating by physicochemical and statistical analyses on available evidences. If evidences are insufficient for modeling, additional evidences are collected by experiments and CFD analysis. The evidences from these two collecting activities have different aspects. CFD analysis can obtain all kinds of evidences on fluid dynamics, but cannot prove that the results are correct in actual. On the other hand, experiments can provide facts on physical phenomena, but have the limitation of the number of results due to the feasibility of experiments. Based on the difference of them, required evidences should be collected by collaborating these methods.

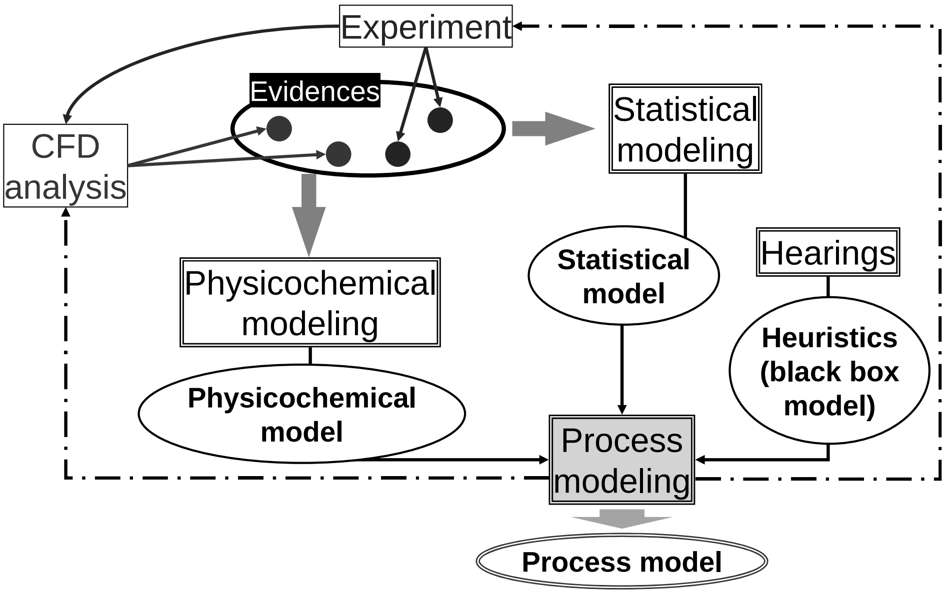


Figure 4-18 Process modeling with available methods

Figure 4-18 also includes the collection of heuristics, which are sometimes represented as black box model. Although such model cannot explain the cause-effect chain physically, it can often indicate numerical facts under specific conditions of process. It can be utilized as the verification information for established process models.

4.4.4. Summarization

This section presents the overviews of the requirements and approaches of process modeling for process simulation in risk-based decision making. Statistical analysis on collected evidences can discover a determinate law of process data under process conditions. Physicochemical analysis can characterize and establish the physical model of the physical phenomena based on the evidences as well as the discovered laws by statistical analysis. Additionally, CFD analysis can be applicable to specify the physical phenomena and substitute for experiments. Developed process models can be verified by referring heuristics represented as black box model.

Various modeling approaches can be applicable for specific process modeling. The effective selection of such available methods is important, which can be called as problem-oriented selection.

4.5. Open-System Process Modeling

4.5.1. Introduction

This section introduces the actual case study of risk-based alternative generation and process simulation. The target of this case study is open-system process, especially ordinary metal cleaning process. Many industries include open-system processes utilizing chemicals. In the results of PRTR investigation 2006, 88.3 % of emission is released into the atmosphere and most of them are released from open-system use (MOEn 2008b). This means that the open-system process modeling for risk reduction is strongly needed for the sustainable chemical supervising.

With regard to analyze open-system process, it is considerably difficult to make just mass and heat balances, because of the existence of free input/output of chemical substances. In contrast to closed-system process, the uncertainty becomes significant in the estimation of process data from process parameters. To reduce the uncertainty possibly, available resources must be collaborated adequately.

Metal cleaning process has aspects as batch process as well as open-system process. For dealing with various metal parts, on-site engineers develop individual ways of handling them. Such uncontrolled manipulations may have great influences on the physical phenomena in washing machine. Major operational conditions are considered as process parameters analyzed in process modeling.

The goal of this section is to develop the process model enabling alternative generation based on evaluation results and process simulation for performing LCA and RA of generated alternatives.

4.5.2. Evidences Collection

About the detail physical phenomena inside of industrial washing machine, there is quite small number of researches and literatures. Historically, the experts in industries have understood them empirically and developed heuristics enabling semi-quantitative process design. Toward more effective and expanded process design, such empirical knowledge is applied into analysis.

First, the dominant process parameters as risk factors in washing machines are specified by analyzing heuristics. Specified parameters might have strong correlation with the emission amount and workplace concentration. Based on such sensitive parameters to risk, the evidences are collected on the relationship between process parameters and risk factors by the investigation on actual sites, the experiments using industrial cleaning machines, and CFD.

Investigation on actual cleaning processes aimed to collect process parameters and data for statistical analysis on the correlations. The planning and collecting experiments can be applicable whole modeling activities. In this study, two industrial machines can be utilized for experiment with a great deal of cooperation from industrial experts, which enables the collection of evidences with high reliabilities on recreating actual cleaning sites. The detail experiments for understanding all physical phenomena inside and outside of washing machines cannot be possible to execute with just two available washing machines. Alternations of hardware specification and installation of peripheral devices are the examples of parameters that are not easily changeable. CFD has the possibilities to replace the experiments alternating such parameters. Furthermore, the movement of fluid inside and outside of washing machine can be visualized by CFD. The knowledge obtained by CFD is innovative for the experts of industrial cleaning. The detail settings and parts of results are organized in **Appendix**.

4.5.3. Qualitative Process Modeling

Through the previous researches on the evaluation of process in use, the risk factors in cleaning process were specified as shown in **Figure 4-19**. These factors are necessary for the evaluation on LCA and RA. Considering such factors, the dominant process parameters were characterized on the basis of heuristics and investigation on actual sites, which are organized in **Table 4-17**. As well as the process parameters, measureable parameters having great influences on the physical phenomena of cleaning processes are organized in **Table 4-17**. Such measureable parameters can be obtained for existing processes even at the early design phases.

In **Figure 4-20**, single-lined boxes represent device components in that type of cleaning process. Double-lined boxes show three major emission styles in solvent cleaning process; ventilated, taken-out, and diffused agents. Ventilated agent is intentionally caused by ventilation system to keep workplace safe and can be emission to the environment directly from workplace. The taken-out emission means the emission from washing machine to inside of cleaning site as liquid agent attached on the surface of them and diffused agent is one from the opening of washing machine to inside of cleaning site.

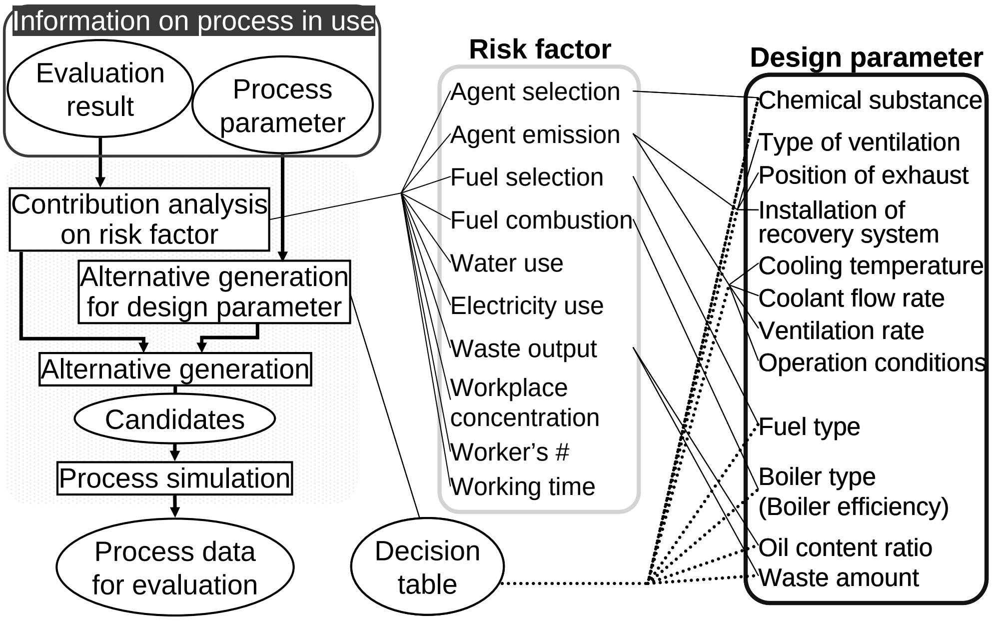


Figure 4-19 Risk factors and decidable/not-decidable parameters in cleaning process

Table 4-17 Dominant process parameter in solvent cleaning process

Dominant process parameter including changeable one in experiment			Measurement parameter and calculation data
Device	Operation	Environment	
▪ Board height in machine	▪ Cooling temperature ▪ Coolant flow rate ▪ Working/idle ▪ Arrangement of metal part ▪ Material of metal part ▪ Shape of metal part ▪ Additional drying time (dwelling) ▪ Takt time	▪ Ambient air flow ▪ Room temperature and humidity (Accordingly possible by performing experiments in different seasons)	▪ Amount of liquid agent in washing machine ▪ Temperatures of each bath ▪ Input/output temperature of coolant ▪ Workplace concentration

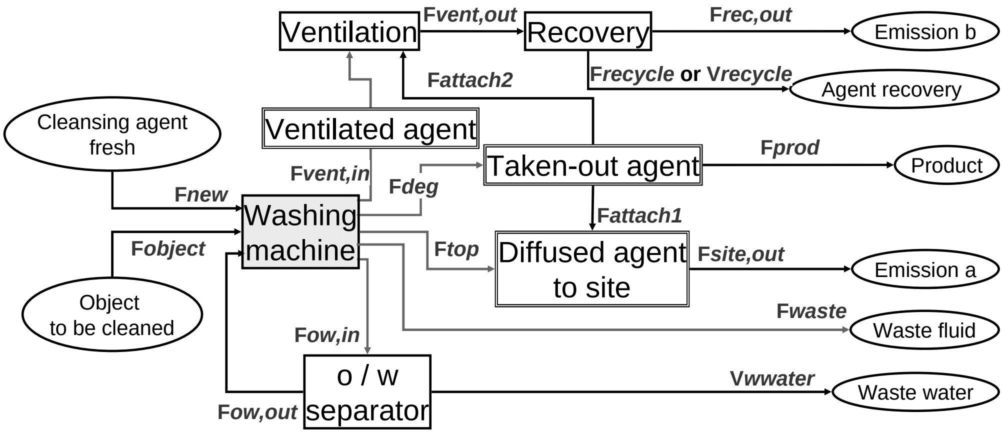


Figure 4-20 Qualitative cleaning process model

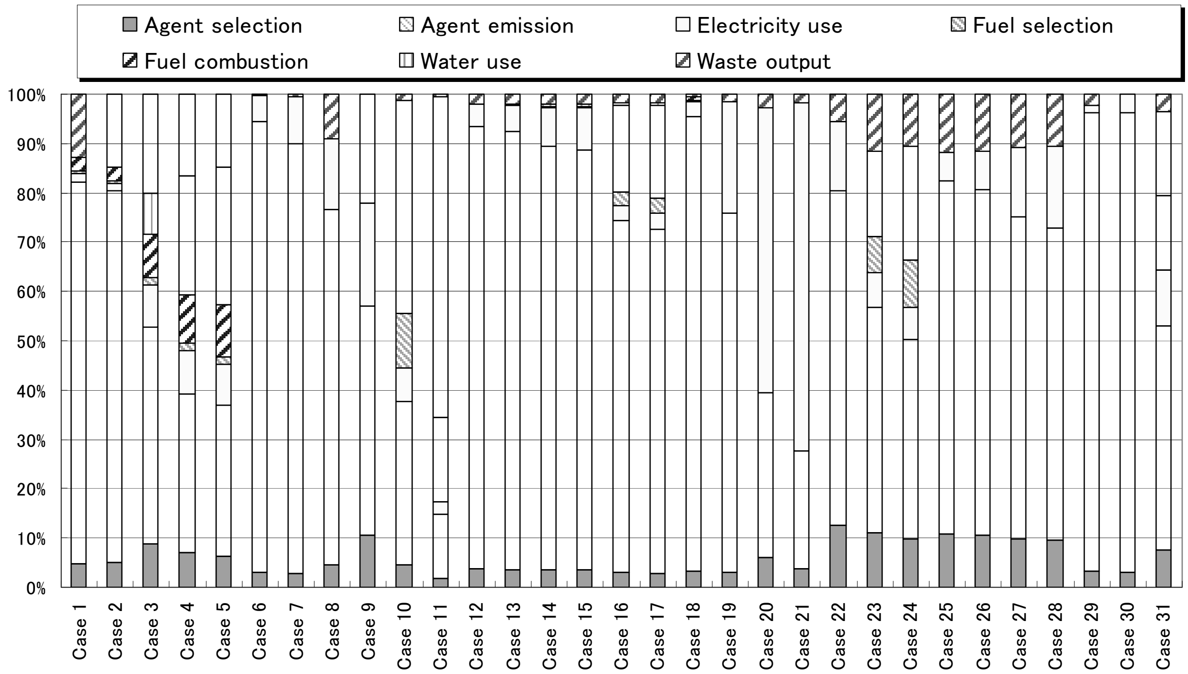


Figure 4-21 Result of contribution analysis on Case 1-31

Figure 4-21 shows the contribution analysis of the evaluation results in Chapter 3. According to the results, the large contribution categories are different from site to site, although the most of them is agent emission. For each risk factor, possible alternative candidates are generated and discussed below. The analyses below were based on heuristics and physicochemical reasoning of evidences. The obtained knowledge was organized as risk-process linkage model as shown in **Table 4-18**.

Agent Selection

Cleansing agents have cumulative environmental impact during the production of them. As shown in **Figure 4-21**, the contribution is not so large. In this regard, however, the emission amount and styles of agent emission originates from the physical properties of chemical substances. In the selection of cleansing agents, as well as those of risk, the aspects of function due to chemical substances should be considered. Therefore, function analysis is needed for the consideration of the alternation of cleansing agent.

Agent Emission

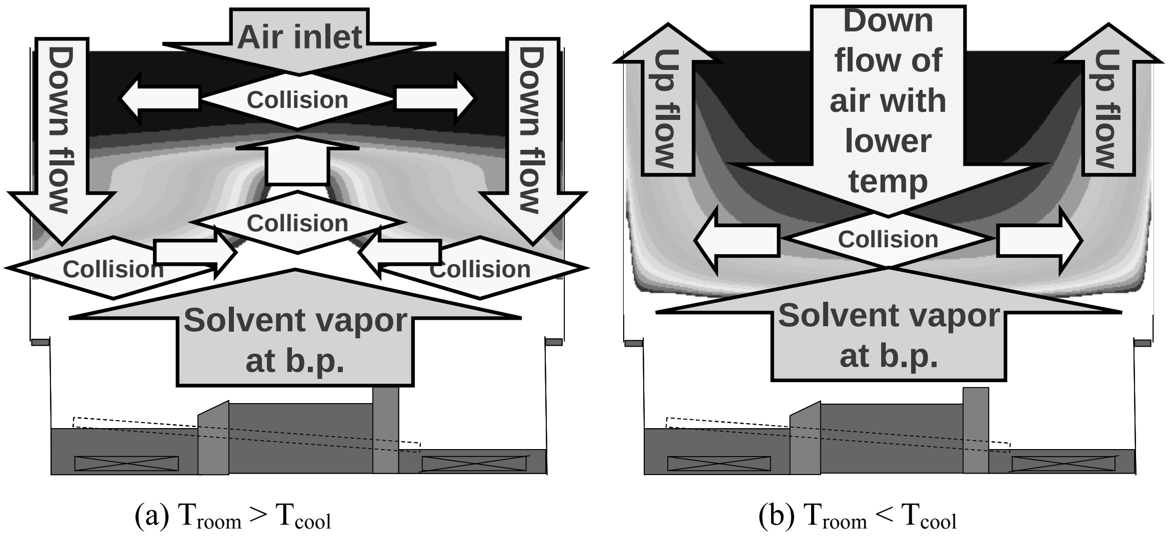
Steady Emission from the Opening of Machine

Because the washing machine is open-system, cleansing agents leak to workplace even in steady-state. To prevent the gaseous agent in washing machine from leaking, the arrangements of process parameters can be alternative candidates.

Cooling efficiency has a strong connection with the leak of cleansing agent. By cooling around the cooling pipes inside of washing machine, the density stratified fluid is created, which can be observed as vapor line in washing machine. In **Figure 4-22**, the vapor line appears around the points where solvent vapor at boiling point collide with air inlet. It was found that the stability of this line is the important key of determining the amount of cleansing agent. The cooling temperature and coolant flow rate have correlation with emission rate (Tomita 2007). The physical phenomenon is changed when the cooling temperature is same as that of room or not (Fujii 2008).

The emission amount of cleansing agent is considerably increased by the ambient air flow. In actual cleaning sites, the factors of ambient air flow can be air conditioners, spot coolers, movements of workers, and winds. Except winds, such factors cannot be eliminated at all. Covers, shields, or other countermeasure must be installed to protect the cleansing agent inside of the open-top washing machine.

There is a required air flow possibly disturbing cleansing agent. Local ventilation system, which is obligated to be installed in cleaning process, causes air flow near the opening of washing machine. Even if the air flow is set as the recommended value of regulation, the emission of agent is stimulated. The influence becomes heavy if the type of local ventilation system is more primitive such as exterior one. Note that the local ventilation system is installed for keeping workplace safe. The excess flow rate may cause the emission more than required. The type and ventilation rate should be arranged under plant-specific conditions.



(a) $T_{room} > T_{cool}$ (b) $T_{room} < T_{cool}$

Figure 4-22 Physical phenomenon inside of washing machine

Table 4-18 Part of risk-parameter linkage model

Process parameter				In process effect				
ID No.				Temporal aspects of effect	physical interpretation of parameter	related physical phenomenon	flow in washing machine	process flow
1302	washing machine	cooling pipe	temperature	non-cleaning / cleaning	cooling temperature inside of machine	condensation of cleansing agent inside of machine	amount of reflux flow	emission volume of cleansing agent from opening of machine to inside of site
1303	washing machine	cooling pipe	flow rate	non-cleaning / cleaning	cooling efficiency inside of machine	condensation of cleansing agent inside of machine	amount of reflux flow	emission volume of cleansing agent from opening of machine to inside of site
1001	washing machine	opening of machine	area	non-cleaning / cleaning	diffusion area from machine to inside of site	diffusion from machine to inside of site	diffusion-emission from machine to inside of site	emission volume of cleansing agent from opening of machine to inside of site
4001	cleaning operation	transportation method	auto/hand	cleaning	effect on disturbance of highly-concentrated vapor	rising of highly-concentrated vapor	emission from machine to inside of site	emission volume of cleansing agent from opening of machine to inside of site
4002	cleaning operation	transportation method	moving rate	cleaning	effect on disturbance of highly-concentrated vapor	rising of highly-concentrated vapor	emission from machine to inside of site	emission volume of cleansing agent from opening of machine to inside of site

Agent recovery system such as activated carbon recovery can be a powerful alternative reducing the emission amount from ventilation outlet. In this regard, however, the low concentration of agent in outlet gas cannot be recovered effectively by such end-of-pipe technologies. The efficiency of the collection of the leaked agent from washing machine by ventilation systems must be improved to reduce emission by this alternative candidate.

Taken-out Liquid Agent by Metal Parts

Cleaning agent has a possibility to be taken out by metal parts as liquid attached on the surface of metal parts. This emission style is caused by the insufficient drying operation inside of the washing machine. The additional drying process after vapor washing bath is referred as dwelling process. The residence time of dwelling should be set adequately to reduce such emission. As well as the dwelling time, the position of metal parts during cleaning operation has a large contribution to taken-out emission. Metal parts sometimes have complicated shapes. Such parts can ladle liquid agent out of washing machine. The arrangement of positioning metal parts can reduce the emission.

Fuel Selection and Combustion

As shown in **Figure 4-21**, fuel combustion has a large contribution to total environmental impact. This is because the SO_x and NO_x due to the combustion of fuel have large potentials to cause human health. To improve this factor, there are two possible alternatives: change the fuel and improve the combustion efficiency.

Originally, the fuel combustion is mainly needed to provide steam in cleaning process. The change of fuel is not big problem, and then, it can be a viable solution to reduce the environmental impact. In this regard, however, the emission amount of NO_x cannot be reduced even if fuel is changed to pure LNG, because the mechanism of creating NO_x highly depends on the efficiency of boiler. The substitution of boiler is required to reduce the emission.

Water Use

Water supply is needed for cooling of washing machine and recovery systems. It is mainly used as process water, almost all amount of it can be recycled in cleaning site. Otherwise, the water emission is increased significantly.

Electricity Use

Electricity is needed for all devices in a cleaning process. Although it has large contribution to total environmental impact, the amount of consumption is not always traced in cleaning sites. To reduce the consumption, unnecessary peripheral devices should be cut off. For example, although many sites install ultrasonic wave, most of them work as one of the heaters in washing machine. In such site, the installed ultrasonic is one of the cause of increasing electricity use and agent emission.

Some sites apply the electric heaters in their washing machines. Electricity can be utilized easily and applicable. In this regard, however, electric heaters may cause heat decomposition of cleansing agent. Indirect heating may be the better way of heating concerning the decomposition.

Waste Output

Waste fluid from washing machine contains cleansing agents and removed impurities. Many cleaning site outsources such fluid to solvent recycling industries, and gets the distilled cleansing agent. The criterion judging the draining periods of waste fluid from washing machine is based on the cleaning requirements. Therefore, the content ratio in waste fluid is different from site to site. The improvement of the criterion link to the reduction in the amount of waste fluid and environmental impact in waste treatment process.

Workplace Concentration

Workplace concentration is the factor of occupational health risk. It is caused by the indoor emission of cleansing agent. To reduce the indoor emission, the distribution ratio of outdoor/indoor emission should be increased. In this time, the total emission amount may be increased by air disturbance due to the enhancement of the ventilation rate. To avoid the undesired results, the installation of recovery system might be effective alternative.

4.5.4. Alternative Generation Associating Knowledge on Process

Table 4-19, **Table 4-20**, and **Table 4-21** organize the decision tables for specifying alternative candidates under process conditions, which are for steady emission from the opening of washing machine, the taken-out emission by objects to be cleaned, and fuel selection and combustion.

Figure 4-23 shematically shows the procedure of the generation of possible alternatives based on decision tables structuring knowldege on process behavior. In this procedure, the running process parameters are converted into a condition vector defined in **Figure 4-13**. The value in the cells of decision table means that “1” or “0” are the state of required conditions and “-“ is not required conditions. If the conditions of targeted process correspond with those of a decision alternative, the effective alternative is indicated in alternative part as shown in **Figure 4-12**. The criterion of conversion fron process parameters into a condition vector and the decision tables are based on the structured knowled on process behavior.

To narrow the available alternatives, the semi-quantitative reduction efficiency is estimated by process model for simulation and organized in **Table 4-22**. This reduction efficiency is the feedback information from process simulation.

This sub-section presents the alternative generation based on process model, where the qualification of physical phenomena can effectively show the possible alternatives based on the evaluation results. Obtained understandings of them can be systematized by organizing them in linkage models. With the systematized knowledge on process, decision table can be developed for integration of them with activities and activation by support mechanisms.

Table 4-19 Decision table of generating alternatives reducing steady emission from the opening of washing machine

Decision alternative	1	2	3	4	5	6	7	8	9	10
T_{cool}: lower than adequate value	1	-	-	-	-	-	-	-	-	-
T_{cool}: near adequate value	0	-	-	-	-	-	-	-	-	-
T_{cool}: higher than adequate value	0	-	-	-	-	-	-	-	-	-
F_{cool}: lower than adequate value	0	1	-	-	-	-	-	-	-	-
F_{cool}: higher than adequate value	0	0	-	-	-	-	-	-	-	-
F_{air}: nearly zero	-	-	0	-	-	-	-	-	-	-
F_{air}: breezing	-	-	0	-	-	-	-	-	-	-
F_{air}: with air conditioning	-	-	1	-	-	-	-	-	-	-
LVS: exterior	-	-	-	-	-	-	-	-	0	0
LVS: enclosed-exterior	-	-	-	-	-	-	-	-	0	0
LVS: enclosed-hood	-	-	0	-	-	-	-	-	1	1
F_{lvs}: lower than standard	-	-	-	0	0	0	0	1	1	0
F_{lvs}: near standard	-	-	-	0	0	0	1	0	0	0
F_{lvs}: higher than standard	-	-	0	1	1	1	0	0	0	1
ARS: install	-	-	-	0	1	1	1	1	1	0
ARS: scheduled maintenance	-	-	-	0	0	0	-	-	-	0
$C_{workplace}$ A: -5 ppm	-	-	-	1	0	1	0	0	0	1
$C_{workplace}$ A: 5-20 ppm	-	-	-	0	-	0	-	-	-	0
$C_{workplace}$ A: 20- ppm	-	-	-	0	-	0	-	-	-	0
$C_{workplace}$ B: -5 ppm	-	-	-	-	0	-	0	-	0	1
$C_{workplace}$ B: 5-20 ppm	-	-	-	-	-	-	-	-	-	0
$C_{workplace}$ B: 20- ppm	-	-	-	-	-	-	-	-	-	0
Adequate increase of T_{cool} may be better	1	0	0	0	0	0	0	0	0	0
F_{cool} should be increased	0	1	0	0	0	0	0	0	0	0
F_{air} should be decreased significantly	0	0	1	0	0	0	0	0	0	0
Installation of ARS is recommended	0	0	0	1	0	0	0	0	0	1
Maintenance of ARS is recommended	0	0	0	1	0	1	0	0	0	1
Taken-out agent should be decreased	0	0	0	0	1	0	1	0	1	0
F_{lvs} should be increased	0	0	0	0	0	0	1	1	1	0
F_{lvs} should be decreased	0	0	0	0	0	0	0	0	0	1

T_{cool}: cooling temperature, F_{cool}: coolant flow rate, F_{air}: ambient air flow rate, LVS: local ventilation system, F_{lvs}: flow rate of LVS, ARS: agent recovery system, $C_{workplace}$: workplace concentration,

Table 4-20 Decision table of generating alternatives reducing taken-out agent by objects to be cleaned

Decision alternative	1	2	3	4	5
Arrangement of positioning metal part	0	-	-	-	1
$T_{dwelling}$: non	-	1	0	0	-
$T_{dwelling}$: more than 1.0 min less than 5.0 min	-	0	1	0	-
$T_{dwelling}$: more than 5.0 min	-	0	0	1	-
$C_{workplace}$ A: -5 ppm	-	-	-	-	0
$C_{workplace}$ A: 5-20 ppm	-	-	-	-	-
$C_{workplace}$ A: 20- ppm	-	-	-	-	-
$C_{workplace}$ B: -5 ppm	0	0	0	0	-
$C_{workplace}$ B: 5-20 ppm	-	-	-	-	-
$C_{workplace}$ B: 20- ppm	-	-	-	-	0
Manual of arranging position should be developed	1	0	0	0	0
Dwelling time should be increased	0	1	1	0	0
Dwelling position should be improved	0	0	1	1	0
Let standing position should be improved	0	0	0	0	1
The way of transferring works should be improved	0	0	0	1	0

Table 4-21 Decision table of generating alternatives reducing risk associated with heating utility

Decision alternative	1	2	3	4	5
Fuel: LNG (or city gas)	1	0	-	-	1
Fuel: LPG	-	-	-	-	-
Fuel: Kerosene	-	-	-	-	-
Electricity for heating	0	0	1	0	0
Steam boiler efficiency: less than 80%	-	-	-	1	-
Steam boiler efficiency: 80-90%	-	-	-	-	-
Steam boiler efficiency: more than 90%	0	-	-	-	-
Fuel should be changed to LNG or city gas	0	1	0	0	0
Change of heating to steam may be better	0	0	1	0	0
Boiler should be renewed to increase efficiency	1	0	0	1	0
Consumption should be adjusted to function	1	0	1	0	1

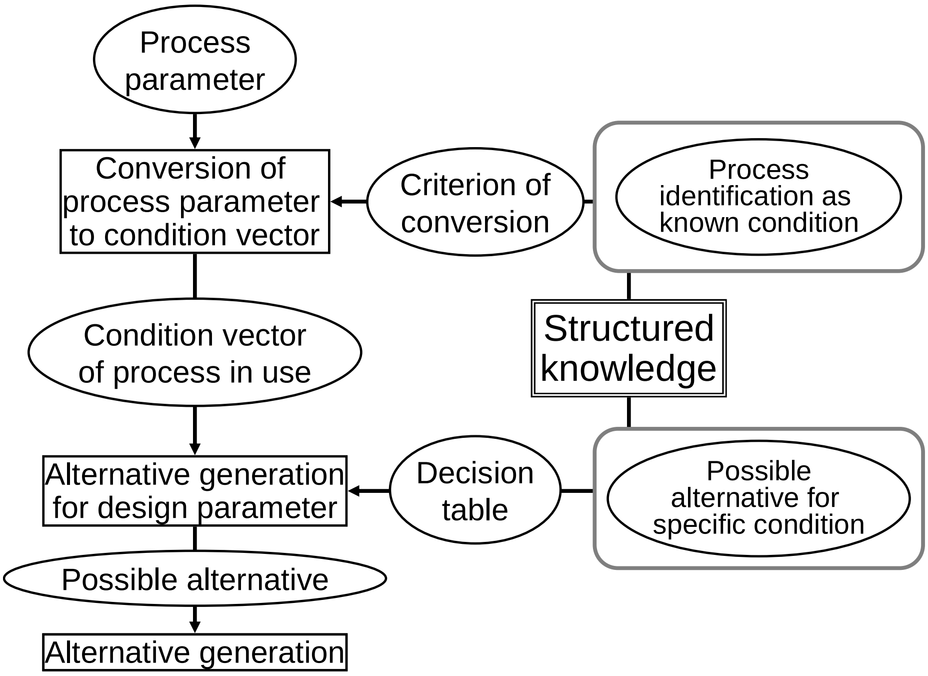


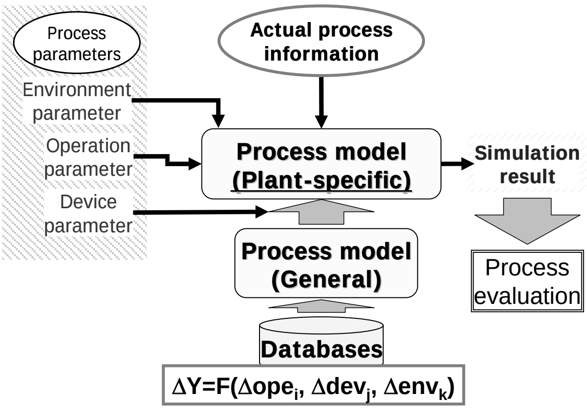
Figure 4-23 Generation of possible alternatives based on decision tables structuring knowldege on process behavior

Table 4-22 Semi-quantification of alternative candidates

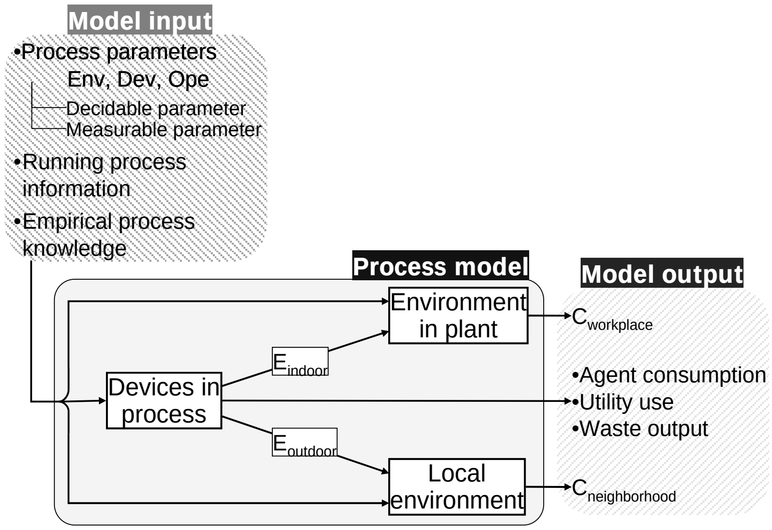
	Maximum reduction ratio	Average rate of change	Intercept	Determination coefficient
T_{cool} (without working)	33.8%	2.87E-03	7.02E-02	8.10E-01
T_{cool} (during working)	57.9%	1.22E-02	6.97E-03	9.98E-01
F_{lvs}	95.1%	9.73E-01	-5.50E-02	7.86E-01
F_{air}	81.1%	2.03E-01	1.52E-01	8.75E-01
$T_{dwelling}$ Fe (plate: no-arranged)	16.5%	-4.38E+00	2.60E+01	8.53E-01
$T_{dwelling}$ Fe(plate: arranged)	83.6%	-2.14E+01	2.22E+01	7.67E-01
$T_{dwelling}$ Fe(block)	85.1%	-1.38E+00	1.41E+00	7.77E-01
Shield installation during machine idle	81.1%	-	-	-

4.5.5. Quantitative Process Modeling

Cleaning process has significantly wide range of the variety of plant-specific conditions, which have large influence on the estimation results. Because it is not feasible to contain all factors in cleaning sites, the extrapolation from existing process can be a viable solution to establish mathematical process model. **Figure 4-24**-(a) shows the process models attainable for estimating process data based on actual process information, which can reduce the uncertainty possibly by utilizing available data at the retrofitting process design phase. For meeting the data requirements of LCA and RA, the workplace concentration is needed with the amount of agent consumption. **Figure 4-24**-(b) illustrates the process model components to estimate process data required for LCA and RA. The model is composed of the module of estimating chemical consumption, the emission amount, and workplace concentration.

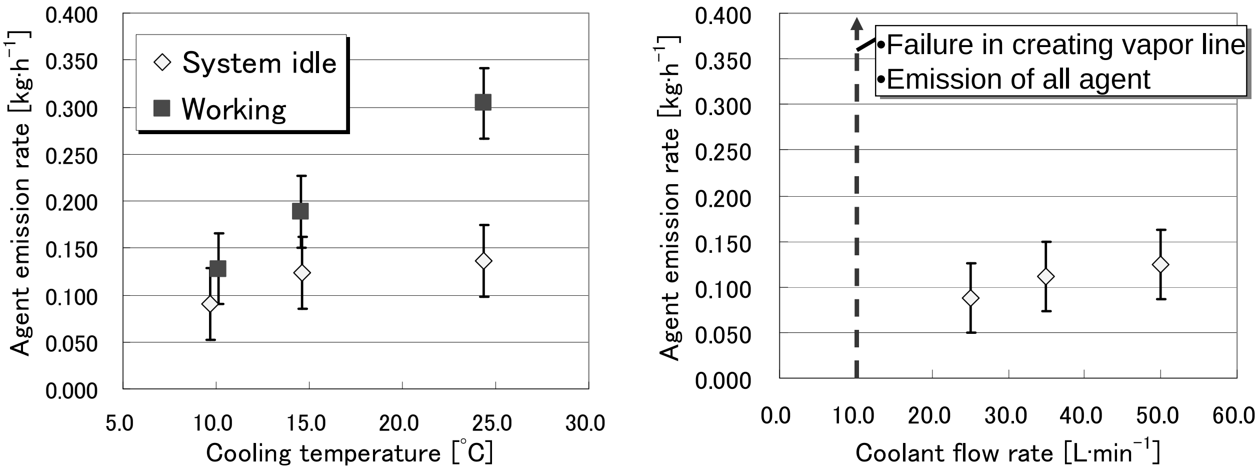


(a) Model overview



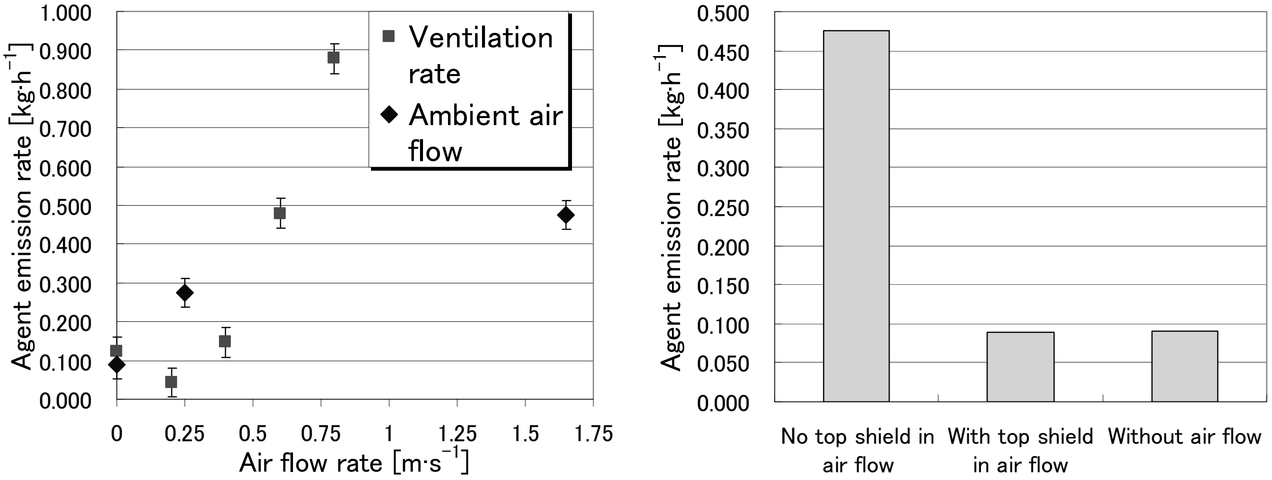
(b) Model components

Figure 4-24 Process models attainable for estimating process data required for LCA and plant-specific RA based on actual process information



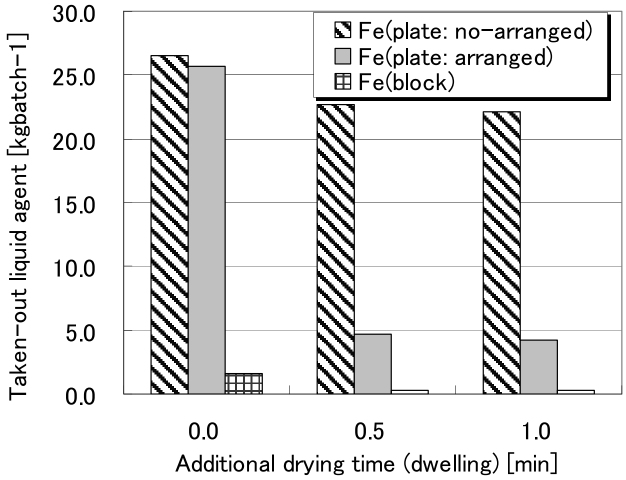
(a) Cooling temperature

(b) Coolant flow rate



(c) Ambient air flow rate

(d) Shield installation



(e) Additional drying time and positioning arrangement

Figure 4-25 Experiment results on the relationship between agent emission rate and process parameters

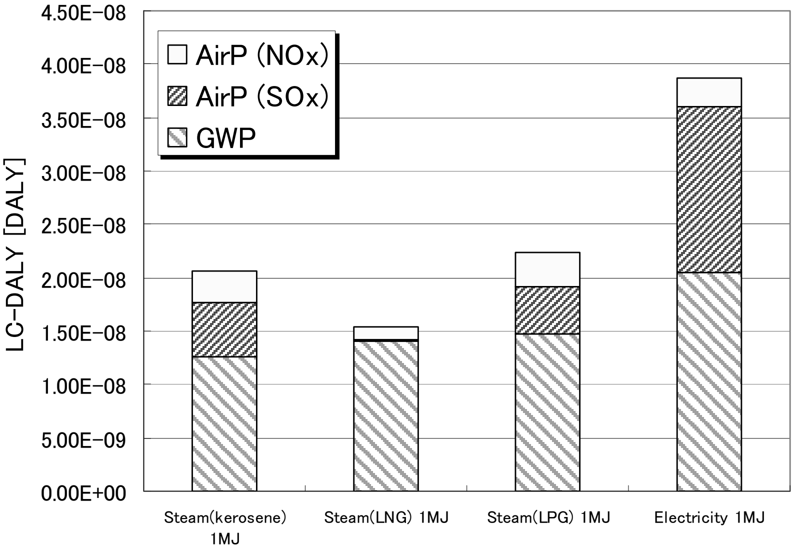


Figure 4-26 LC-DALY related with utilities in cleaning site

Chemical Consumption and Emission Amount

Process parameters dominating the chemical consumption and emission amount have already specified in the qualitative process modeling. Based on such parameters, experiments using industrial cleaning machines were conducted and the results of them are partly shown in **Figure 4-25**. The vertical axis indicate the absolute value in experiments in **Figure 4-25**. This can be recalculated as relative values comparing to the maximum emission rate. The potential reduction ratio in **Table 4-22** was obtained by this approach. If the existing process data is available, the estimation can be calculated by using the generated alternatives and the reduction ratio from **Figure 4-25**.

Figure 4-26 shows the cumulative environmental impact of productions for unit heat demand by steams from three fuels and for electricity unit of which is converted into MJ. Based on the three major emissions, the total production DALYs are different, and the best style is the steam from LNG..

Workplace Concentration of Chemical Substances

To estimate workplace concentration, the emission of cleansing agent should be traced. **Figure 4-27** shows emission factors and ventilations inside of the workplace. The nomenclature, AE, means the agent emission from washing machines. Emission factors contribute to the increase of local concentrations and can be mainly divided into three styles of emission: indoor emission (AE_{indoor} [kg·hr^{-1}]), outdoor emission ($AE_{outdoor}$ [kg·hr^{-1}]), and content of waste fluid (AE_{waste} [kg·hr^{-1}]). AE_{indoor} is the emission released from washing machine into workplace, which is the cause of the increase of workplace concentration (C_{work} [mg·m^{-3}]). It is divided into the diffusion of gas-phase agent from the opening of washing machine to workplaces (AE_{diff} [kg·hr^{-1}]) and the taken-out emission from washing machine by metal parts as liquid-phase agent attaching on the surface of cleaned metal parts (AE_{taken} [kg·hr^{-1}]). $AE_{outdoor}$ is composed of two styles: the direct release of the aspirated agent through local ventilation system (AE_{vent} [kg·hr^{-1}]) and the emission from workplace to the environment on room air exchange (AE_{exch} [kg·hr^{-1}]). AE_{waste} is the emission factor as the liquid-phase agent included in the waste fluid periodically drained from washing machine.

The model prediction has considerable uncertainties based on two aspects of calculation. First, the background concentration in workplace has large uncertainty and difficult to be estimated. Such concentration has wide range based on the measurement points as shown in **Figure 4-28**, and various aspects of cleaning site must be considered to estimate such background concentration. The second factor of uncertainty is the difficulty of estimating AER. Air exchange can be stimulated by air conditioning and open/close of windows and doors. Rigorous modeling of these factors is not feasible for each plant.

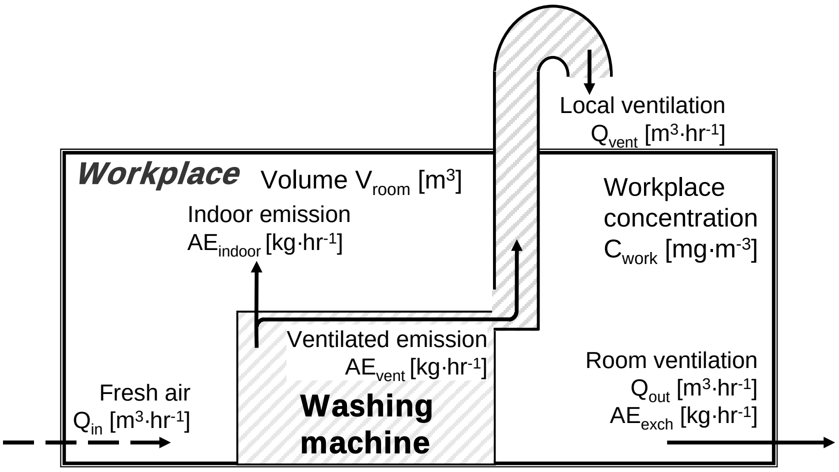
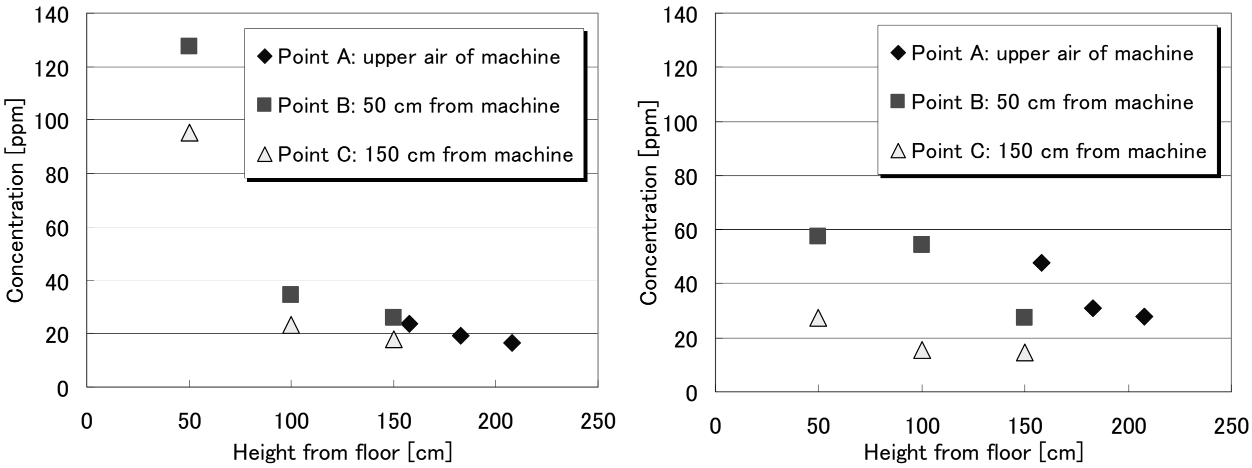


Figure 4-27 Plant process model



(a) Start up at 9 am

(b) During operation at 2 pm

Figure 4-28 Concentration distribution in the room where cleaning process is located. The measurement points are shown in **Appendix**.

To cover the large uncertainty of the emission ratio between indoor and outdoor, available actual data is applied for the estimation. Originally, emission amounts are calculated by the available data on site as shown below.

$$AE_{gas} = AC - Dis. \qquad \textbf{(4-4)}$$

where AE_{gas}[kg•day^{-1}]: gas-phase agent emission, AC[kg•day^{-1}]: agent consumption and Dis. [kg•day^{-1}]: displacement of agent such as agents included in waste fluid and adsorbed on activated carbon. AE_{gas} means the total emission, which can be divided into the emissions to microenvironment or the environment, or indoor and outdoor as shown below.

$$AE_{gas} = AE_{indoor} + AE_{outdoor} \tag{4-5}$$

where AE_{indoor} [kg•day^{-1}]: gas-phase agent emission to the indoor environment and $AE_{outdoor}$ [kg•day^{-1}]: gas-phase agent emission directly to the outdoor environment. The distribution factor of indoor to total emissions can be quantitatively-expressible by process conditions X.

$$\frac{AE_{indoor}}{AE_{gas}} = D(X) \tag{4-6}$$

where D(X)[-]: the distribution factor of indoor to total emissions. In this regard, however, AE_{indoor} cannot be directly measured easily. Consequently, indoor concentration, which is measurable parameters and the function parameter of AE_{indoor}, is adopted as the comparative parameter to specify the relationship between local risks and global impacts.

$$\frac{C_{indoor}}{AE_{gas}} = D'(X) \tag{4-7}$$

where D'(X)[mg•m^{-3}•(kg•day^{-1})$^{-1}$]: the distribution factor of indoor concentration to total emissions. C_{indoor} is workplace concentration and one of the parameters of calculating PDI_{worker}. The relativity analyses are conducted between AC and PDI_{worker} on measured process conditions in the following.

Plant-based interpretation of process

Obtained results were interpreted on the basis of plant-specific and generic conditions. **Figure 4-29** organized the results of relativity analyses between AE_{gas} and PDI_{worker}s on each investigated process based on cleansing agent, metal parts shape, process phase of cleaning, throughputs, local ventilation type and recovery system. For some conditions the relativities were confirmed, linear approximation was conducted by least-square approach, where all intercepts were set as 0. The results of regression analyses were organized in **Table 4-23** and **Table 4-24**.

Cleaning agent

Because of the higher ability of degreasing, TCE has more widely been adopted for precise cleaning processes. The diffuseness of cleansing agent might be dominated by the physical properties of utilized chemical. As shown in **Figure 4-29**-(a), however, the small dependency originated in the difference of chemical was demonstrated between AE_{gas} and PDI_{worker}. This can be attributed to the fact that each process managed to keep the workplace concentrations of them under the standard control values. By the operational efforts, workplace concentrations are controlled safe rather than the expectation based on the diffuseness of chemicals. Because the chemical substances have been considered to have small correlations with AE_{gas}-PDI_{worker} relations, the regression analyses were not performed for **Figure 4-29**-(a).

Characteristics of cleaning process

The number of the cleaning processes having utilized chlorinated solvents has been reduced because of the voluntary management of large enterprises avoiding chlorinated chemicals. Most of the remained processes utilizing such chemicals are the processes where cleaning requirements cannot be achieved without chlorinated solvents. As shown in **Figure 4-29**-(b) and (c), chlorinated solvents are needed to achieve the cleaning requirements of the pretreatment process of metal parts with fine and blind pores before metal surface treatment. Despite the small throughputs and AE_{gas}, such cleaning processes have comparatively high workplace concentrations shown in **Figure 4-29**-(d). This is because the shapes dominate the distribution of AE_{gas} to PDI_{worker}. The overlapping of small parts is regarded as the factors increasing AE_{indoor} by bringing up the cleansing agent from washing machines to the workplace. The same reason can be applied to the metal parts with fine and blind pores. The cleansing agent penetrating the interspaces between parts and pores are considerably difficult to dry out, and then, they are brought out and released into workplace. On the other hand, there are some cleaning processes after cutting or pressing processes. The cleaning requirements are also high enough to utilize chlorinated solvents, because of the finishing phase of manufacturing, the enhancement of electric conducting property and the use as domestic houseware. These products have the shape increasing the brought-out solvents by metal parts such as large or pod types.

According to the regression analyses organized in **Table 4-23** and **Table 4-24**, some process parameters might have correlations with the relation between AE_{gas} and PDI_{worker}. Although there are small determination coefficients in some process conditions, metal parts shape, process phase of cleaning and throughputs were confirmed as the factors to determine the distribution factors D(X) in **Equation (4-7)**. Cleaning processes as pretreatment process have larger potential to increase workplace concentration with the same AE_{gas} than that as post treatment processes. This is because the higher cleaning requirements must be achieved in pretreatment processes.

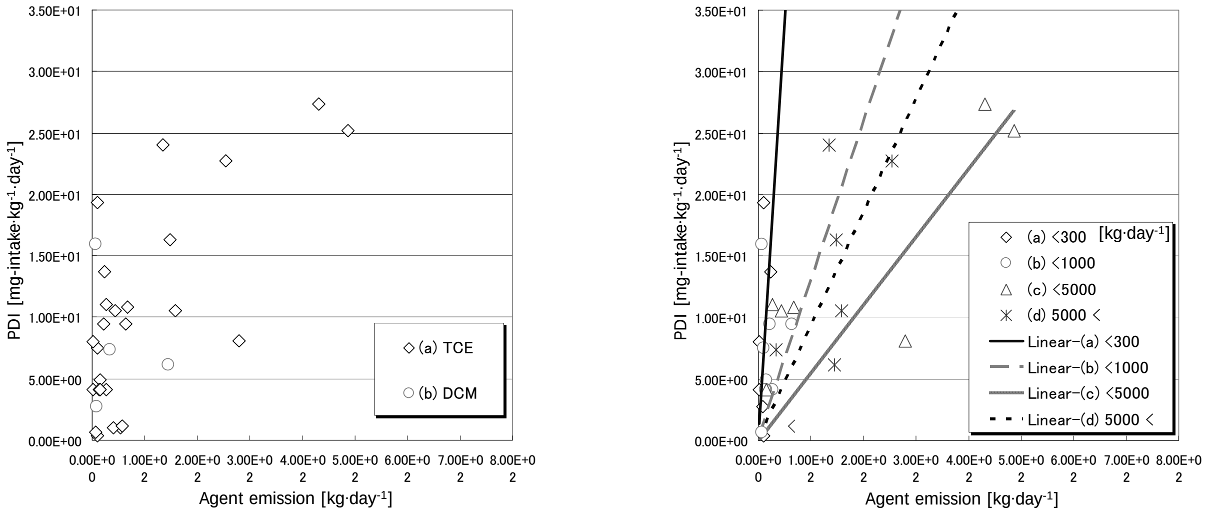
As mentioned above, the characteristics of cleaning process have non-negligible correlations with AE_{gas} and PDI_{worker}, although they are derived from the constraints from the other life cycle stages.

Local ventilation and recovery system

Figure 4-29-(e) shows the correlation of local ventilation system. The results demonstrate that the type of local ventilation device has strong connections with emission and concentration.

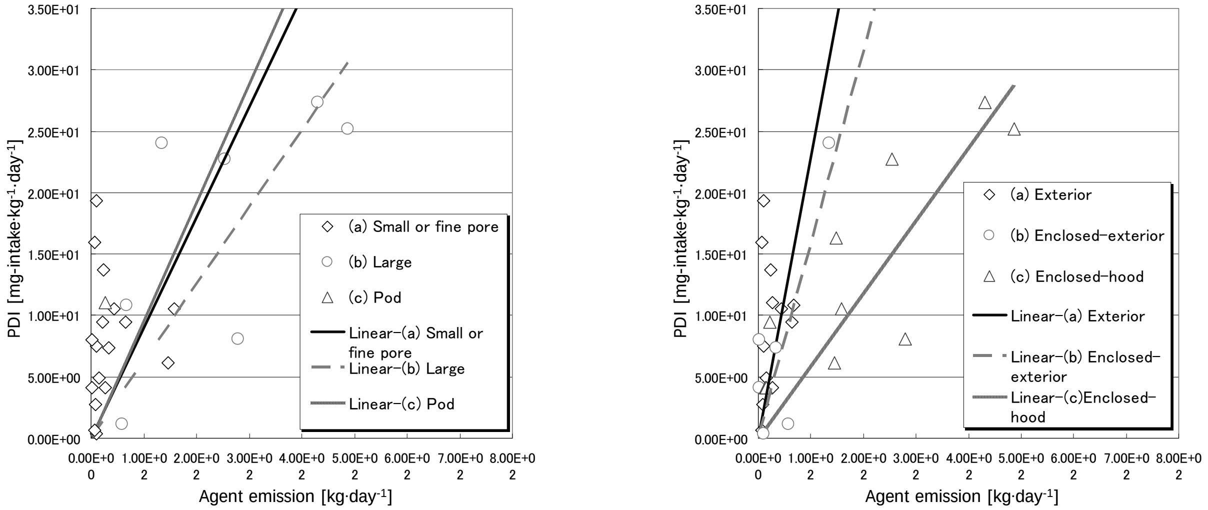
Exterior ventilation as shown in **Figure 3-7**-(a) is one of the simplest ventilation, the inlet of which is located near the opening of washing machine. This type of ventilation sometimes causes the strong disturbance of inside agent and flies up such agent, and then, increases the workplace concentration with small agent emission. Enclosed-exterior type ventilation (**Figure 3-7**-(b)) is the improved exterior type, which has the inlet enclosing the opening of washing machine. This can effectively collect gas phase agent running off the edge, because it is heavier than air. Enclosed-hood type ventilation (**Figure 3-7**-(c)) has the all-enclosing hood to collect all routes of agent emission including liquid agent brought out by metal parts, which cannot be easily trapped by enclosed-exterior type. These features are corresponding with the results in **Figure 4-29**-(e). With the same agent emission, workplace concentrations on sites installing local ventilation system are decreasing in the following order: exterior, enclosed-exterior and enclosed hood type ventilation systems. The determination coefficients of them are high enough to confirm the strong correlations with the distribution factor D(X).

With regard to local ventilation efficiency, the recovery system should be addressed as one of the possible alternative technology. The relationship can be found in **Figure 4-29**-(f). Recovery system is the end-of-pipe technology, which can reduce the agent emission after emitting it from washing machine. This means that such technology cannot reduce the emission from washing machine, but collect the emitted agent through the exhaust pipe. To increase the recovery amount, the concentration and amount of agent in exhaust pipes should be increased, which can be fulfilled by contriving the way of ventilation. Therefore, the recovery system has consequential connections with the distribution factors of indoor and outdoor emissions. The regression analysis was not performed on the recovery system.



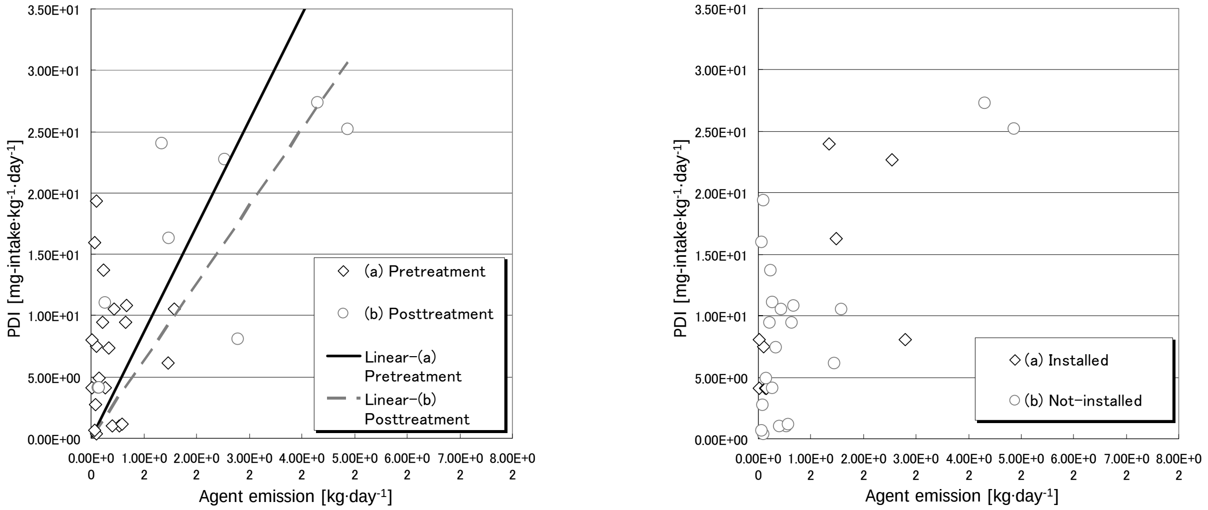
(a) Cleansing agent

(d) Throughputs



(b) Metal parts shape

(e) Local ventilation type



(c) Process phase of cleaning

(f) Recovery system

Figure 4-29 Relationship between total agent emission and PDI based on plant-specific conditions

Table 4-23 Results of regression analyses between total agent emission and $\text{PDI}_{\text{worker}}$ with regard to metal parts shape and process phase

	Metal parts shape			Process phase	
	Small or pore	**Large**	**Pod**	**pre-**	**post-**
Coefficients	8.99E-02	6.28E-02	9.60E-02	8.64E-02	6.30E-02
Standard Error	3.42E-02	1.09E-02	6.30E-02	2.85E-02	1.03E-02
t Stat	2.63E+00	5.79E+00	1.52E+00	3.03E+00	6.14E+00
P-Value	1.83E-02	6.72E-04	1.88E-01	6.55E-03	1.70E-04
Multiple R	5.49E-01	9.09E-01	5.63E-01	5.61E-01	8.99E-01
R Square	3.01E-01	8.27E-01	3.17E-01	3.15E-01	8.07E-01
Adjusted R Square	2.39E-01	6.84E-01	1.17E-01	2.65E-01	6.96E-01
Standard Error	8.08E+00	8.50E+00	4.89E+00	7.43E+00	7.98E+00
Observations	17	8	6	21	10

Table 4-24 Results of regression analyses between total agent emission and PDIworker with regard to throughputs and local ventilation type on site

	Throughputs [kg/day]				Local ventilation type		
	<300	**<1000**	**<5000**	**5000<**	**Ext**	**Enc-ext**	**Enc**
Coefficients	6.77E-01	1.29E-01	5.48E-02	9.21E-02	2.29E-01	1.57E-01	5.87E-02
Standard Error	2.50E-01	5.98E-02	9.72E-03	1.63E-02	6.84E-02	3.63E-02	6.43E-03
t Stat	2.71E+00	2.16E+00	5.64E+00	5.65E+00	3.35E+00	4.32E+00	9.12E+00
P-Value	4.20E-02	5.64E-02	1.33E-03	1.32E-03	6.51E-03	7.59E-03	9.54E-07
Multiple R	7.72E-01	5.63E-01	9.17E-01	9.18E-01	7.10E-01	8.88E-01	9.35E-01
R Square	5.96E-01	3.17E-01	8.41E-01	8.42E-01	5.05E-01	7.88E-01	8.74E-01
Adjusted R Square	3.96E-01	2.17E-01	6.75E-01	6.75E-01	4.14E-01	5.88E-01	7.91E-01
Standard Error	7.26E+00	6.21E+00	6.93E+00	6.42E+00	7.83E+00	5.50E+00	5.14E+00
Observations	6	11	7	7	12	6	13

Table 4-25 AIC analysis of the relativity analyses between AE_{gas} and $\text{PDI}_{\text{worker}}$

	Metal parts	Process phase	Throughputs	Local ventilation	Base
Σe2	1.67E+03	1.68E+03	1.18E+03	1.14E+03	1.71E+03
n	31	31	31	31	31
k	3	2	4	3	1
AIC	1.30E+02	1.28E+02	1.21E+02	1.18E+02	1.26E+02

Relationship between agent emission and $\text{PDI}_{\text{worker}}$

According to the results of regression analyses shown in **Table 4-23** and **Table 4-24**, the type of local ventilation system has a stronger correlation with the relationship between AE_{gas} and $\text{PDI}_{\text{worker}}$ than do the other process conditions on which the regression analyses were conducted. Apparently, local ventilation has been regarded as one of the most dominant factors in agent emission in industry. Although the correlation is smaller than that of local ventilation, other process conditions have some relationship with the distribution factor D(X).

To validate the results of the regression analysis, the comparison of the established approximation line was conducted on the basis of the Akaike information criterion (AIC) shown in the following equations. AIC has been applied to compare models in process engineering (Arora et al. 2001; Conner et al. 2005). A smaller AIC means a higher validation of the model. In this study, the residual sum of squares obtained using the regression analysis tool in Microsoft ® Excel was adopted for the calculation of the maximum likelihood function.

$$\mathrm{AIC} = -2 \times \log(\text{max of likelihood function}) + 2 \times \mathrm{k} \tag{4-8}$$

$$\log(\text{max of likelihood function}) = \mathrm{n} \log\left(\frac{\sum \mathrm{e_i}^2}{\mathrm{n}}\right) \tag{4-9}$$

Here k is the number of variable parameters, n is the number of observations, and $\sum \mathrm{e_i}^2$ is the residual sum of squares. AIC calculations were executed on the basis of multiple relativity analyses grouped into metal parts, process phase, throughput, and local ventilation. The residual sum of squares from each multiple regression analyses is utilized.

Table 4-25 organized the AICs of grouped relativity analyses. As a reference value for each AIC, a regression analysis without process conditions was performed and the AIC value was added to **Table 4-25**. According to the results, local ventilation and throughput were statistically proven to be factors characterizing the correlation between $\mathrm{PDI_{worker}}$ and $\mathrm{AE_{gas}}$. On the other hand, the AICs of metal parts shape and the process phase of cleaning were more than that of the base, which means that these conditions have a weak statistical correlation with the distribution factor. In this regard, however, the slight difference among their AICs cannot ensure that they do not correlate with the distribution factor D(X). This is because the raw process data has uncertainty that brings about a change in the AICs.

The D(X) can be interpreted as a composite function of plant-specific conditions. At the same time, plant-generic conditions, such as the standard control values determined by regulation, have forced on-site engineers in order to change the process parameters to achieve the requirements, which resulted in the change in D(X). Although the AIC value can be an index to judge which conditions should be taken into account, a sufficient understanding of the process must be provided to determine a model. As well as plant specification, the characteristics of industrial sectors, including related laws and regulations, should be considered when addressing the relationship between local risks and global impacts.

4.5.6. Conclusion

For alternative generation and evaluation based on the evaluation results of process in use, the requirements of process models were defined, and they were developed through analyses including experiments using actual industrial machine and CFD analysis. For risk-based generation of alternative candidates, a physical linkage model was developed. This model can reveal the physicochemical and mechanical relationship between process system parameters and function/risk. Based on the revealed logical relationship, alternative parameters can be assumed to reduce targeted risks with keeping enough process system function. Linkage model associating knowledge on process and evaluation methodologies enables the recognitions of each risk reduction by alternatives. Toward such association, quantitative process modeling should be able to consider the process system parameters in linkage models. Process system parameters are divided into device, operation and environment to address and evaluate chemical risks. Effective alternative generation and evaluation needs physical and mathematical models of targeted process systems.

Based on the needs from evaluation methodologies and alternative generation, the quantification of process models by physical analysis was addressed and executed for industrial cleaning processes. Dominant risk factors and process parameters to them can be specified by the contribution analysis on evaluation results of process in use and the investigations on empirical knowledge, respectively. Based on the specified information, physical phenomena occurred in process should be grasped by utilizing all available mechanisms. CFD analysis has a large potential to visualize and understand important fluid dynamics in open-system process modeling. At the same time, experiments can indicate powerful mathematical facts on the relationship between process parameters and physical phenomena. In this regard, however, the empirical knowledge is useful to make effective plans of experiments, especially in open-system modeling. Because an evaluation should include the occupational and neighborhood risks around all processes in a life cycle, local concentrations must be estimated by using emission volumes. In this regard, however, the uncertainties of estimations become a critical factor of miscalculation, because local risks are considerably sensitive to process data. For such highly uncertain modeling, statistical approaches can indicate compromised mathematical models. In this time, empirical knowledge should be implemented into the specification of parameters, because there can be lots of data doubtful as one dominating risk factors.

The variety of cleansing agents, the characteristics of cleaning process, and local ventilation with recovery system were targeted as the plant-specific conditions dominating the distribution factors of indoor and total emission amounts. The relativity analyses could confirm the strong correlations of such process conditions to the agent emission and concentration in microenvironments. According to the AIC calculations for the conditions, local ventilation system and throughputs on sites have effective correlations to address the distribution factors of indoor and outdoor emissions. In this regard, however, as well as statistical approaches, well-understandings of process must be provided to decide process parameters to be included and develop a model. Although the optimal point balancing the process functions and agent emissions might be difficult to find out, the current conditions should be analyzed with the risks originated with agent emission. This paper demonstrates that local risks, especially in microenvironments such as workplace and neighborhood, have strong connections with plant-specific conditions. For an appropriate implementation of microenvironments' impacts practically, as well as plant-specification, the characteristics of industrial sectors including related laws and regulations should be taken into account to address them from agent emissions which can be obtained in ordinary LCI. Otherwise, the data collected in LCI should be expanded enough to estimate the requirements or specify a model to be applied.

4.6. Risk Interpretation on Available Results

4.6.1. Introduction

Decision maker should be able to interpret evaluation results representing local risk and global impact attributable to their own decision. For the appropriate risk interpretation, sufficient referable information is needed to be available for decision makers. At that time, such supports must be carefully considered along the procedure of interpretation approaches to avoid the completely subjective decision and the no practicable one neglecting plant-specific constraints.

This section presents the method of interpreting evaluation results for decision making. The supporting information for appropriate risk interpretation is also addressed. In this sections, the evaluation results are based on the previous results shown in section 3.3.

4.6.2. Association of Knowledge on Interpretation Approach

Figure 4-30 illustrates the procedure of risk interpretation. This approach has two phases of interpretation, which are the approaches on understanding physical meanings of risk and comparing evaluation results. The first step is needed for making acceptances on evaluated risks. The acceptance should be based on the physical meanings of indicated risks. The supporting information on such meanings must be available. If there is any unacceptable risks in all alternatives, the decision cannot be made, and then, further improvements of process are considered. If all risks can be acceptable, the interpretation phase proceeds to the second step, numerical comparing. In this step, the quantified risk indicators are compared numerically, where the less, or more, is better. If there is any trade-off relationship, the optional method for such comparison can be applicable such as grouping, normalization, and weighting. Possible interpretation is discussed in the followings.

Approach on the Basis of Understanding Physical Meaning of Evaluation Result

The physical meanings of evaluation results depend on the way of evaluating them, the hazard, and other physical and technical data applied in the calculation. In many evaluation indicators such as the potential impacts in LCA, the value of results focus on the relative comparisons rather than the absolute judgments. This is because the impact factors enabling the quantification of global environmental impact have large uncertainty due to the assumptions in their calculation. In RA, the hazard data is utilized for the quantification of local risk. Therefore, the indicators have keep physical meaning and can be judged whether the value is acceptable as discussed in section 3.3.

In addition to the meanings attributable to the quantification of evaluation indicators, the targeted categories of evaluation can be one of the important points in risk interpretation. It can be analyzed by the risk categorization matrix shown and discussed in section 4.2. **Figure 4-31** shows the evaluated risk indices and indicators at process evaluation of metal cleaning in section 4.2. In RA of local risk, the indicator, $DALY_{actual}$, utilized $NOAEL_{animal,sub\text{-}chronic}$ by extrapolating it to $NOAEL_{human,chronic}$. In the calculation, the medium- and long-term exposures are assumed to have the same risk. On the other hand, in LCA, $DALY_{marginal}$ was applied for quantifying the human health potential impacts originating from multiple impact categories having different spatially and temporally aspects as shown in **Figure 4-31**. Based on such meaning of evaluation results, the completeness of evaluation can be addressed as risk interpretation. For example, the evaluation is not completed for the decision makers who need all kinds of risk occurred by decisions, because the safety and local environmental risks by chlorinated agents are not evaluated.

For judging the acceptance of evaluation results, the comparison with representative values can be an applicable approach, although it does not lead to the physical understandings of evaluation indicators. **Figure 4-32** shows the comparison of LCA results on a digital duplicator and averaged cleaning process of metal parts composed of it. It is possible criterion for judging the acceptance of risk that the total impact of metal cleaning should be less than 20 % of that of assembled product.

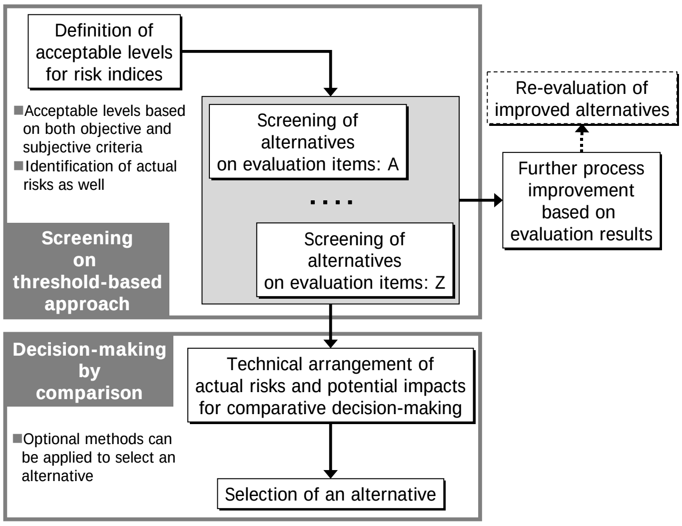


Figure 4-30 Procedure of risk interpretation including approaches understanding physical meanings of risk and comparing evaluation results

As shown above, the step in screening alternatives on evaluation items needs the physical meaning of evaluation indicators. For making this step effective, the selection of evaluation indicators are carefully considered. Otherwise, the acceptance cannot be discussed meaningfully, and it may result in the fault of decision, even if all alternatives cannot reduce risk sufficiently.

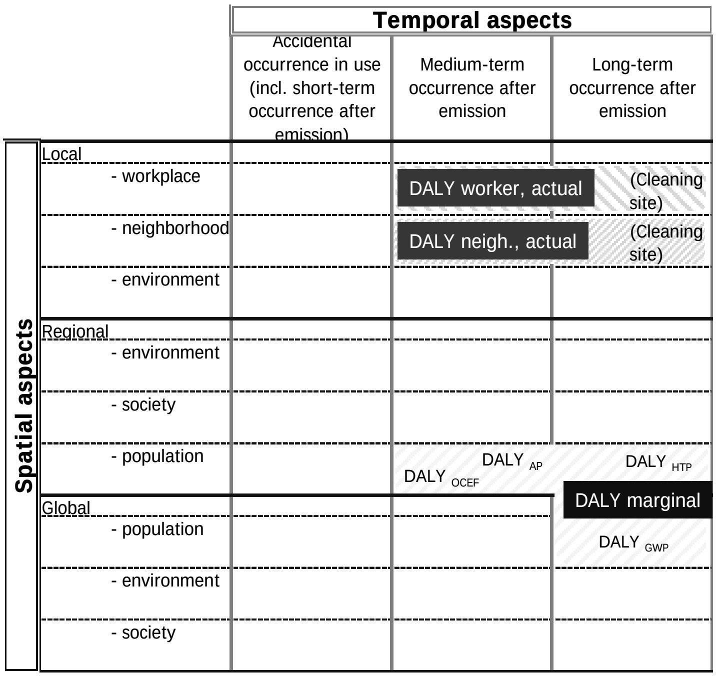


Figure 4-31 Evaluated risk indices and indicators in process evaluation of metal cleaning

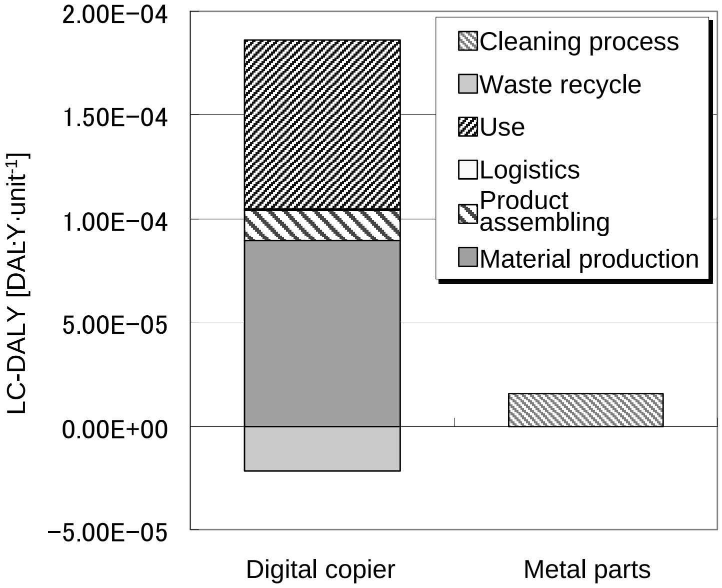


Figure 4-32 LC-human health impacts associated with the life cycle of a digital duplicator and the cleaning processes of metal parts implemented in the duplicator

Approach on the Basis of Comparing Results Numerically

If all risks can be acceptable for decision makers, the comparison of alternatives numerically is the way to decide an alternative process. Because there is sometimes trade-off relationship among evaluation results, the comparison may not be performed simply. The major method for dealing with this problem is the grouping, normalization, and weighting of quantified evaluation indicators. At the evaluation in section 3.3, the evaluation results have been already grouped into local risk, global impact, and economic feasibility. At this time, the results of economic feasibility were converted into the profit in 3 years later after installing alternative candidates by the initial and the running cost. The normalization of these evaluation indicators are based on **Equation (4-10)**. The total scores by weighting each evaluation indicator are represented as **Equation (4-11)**.

$$\mathrm{EI}_{\mathrm{i}}^{\mathrm{Normalized}} = \left(\mathrm{EI}_{\mathrm{i}} - \mathrm{EI}_{\mathrm{min}}\right) / \left(\mathrm{EI}_{\mathrm{max}} - \mathrm{EI}_{\mathrm{min}}\right) \tag{4-10}$$

$$\mathrm{Total\,Score}_{\mathrm{i}} = \mathrm{w}_{\mathrm{a}} \cdot \mathrm{EI}_{\mathrm{a,i}}^{\mathrm{Normalized}} + \mathrm{w}_{\mathrm{b}} \cdot \mathrm{EI}_{\mathrm{b,i}}^{\mathrm{Normalized}} + \mathrm{w}_{\mathrm{c}} \cdot \mathrm{EI}_{\mathrm{c,i}}^{\mathrm{Normalized}} \tag{4-11}$$

where w is the weighting factor of each evaluation indicator. For industrial decision makers, economic feasibility and local risk might be dominant concerns, and the default settings of weighting factors can be (0.2, 0.3, 0.5) for (global impact, local risk, economic feasibility). Because the total scores changed by modifying the three weighting parameters, the representation of total scores with different weighting factors on triangle are useful for the sensitivity analysis of them (Sugiyama 2008), and shown in **Figure 4-33**.

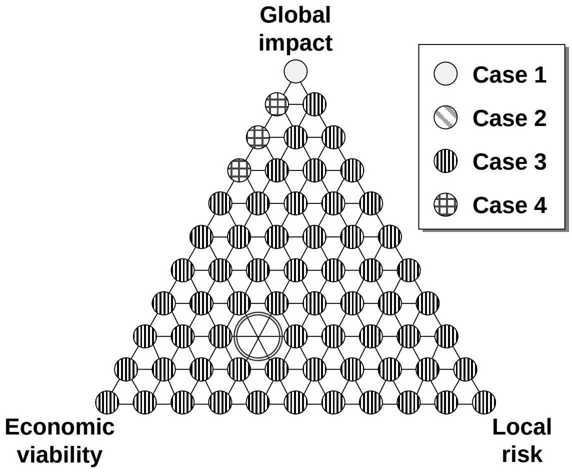


Figure 4-33 Weighting approach to compare different indicators

The results demonstrate that the default settings of weighting factors, (0.2, 0.3, 0.5), and around it decide the alternative candidate as case 3 in **Figure 3-15**, **Figure 3-16**, and **Figure 3-17**. In this results, the case 1 will be selected if the weighting factors focus on only global impact. Case 3 can be selected with the weighting factors for largely global impact, slightly local risks, and no economic feasibility. Case 2 will not be selected by any weighting patterns in the evaluation results.

Weighting approach is one of the strong methods to compare trade-off results. In this regard, however, the weighting can be effectively applied for the quantitative indicators. The qualitative results such as installation feasibilities cannot be implemented into the comparison. Furthermore, the evaluation results may not demonstrate large difference between alternatives at the settings of weighting factors around the points where the optimal alternative is changed. The decision based on weighting approach should be carefully made with understandings of all evaluation results and the second placed alternatives at the selected weighting.

4.6.3. Requirements of Redesigning Process and Scenario

If no risks can be acceptable for decision makers, redesigning process is required for reducing risk. It is the further improvement of process by applying additional or other technologies in alternative generation. In addition to such alternative generation, alternative scenario developments can be applicable and effective methods of understanding and reducing risk. There are two situations of scenario development. First, when there are alternative points attributable to risk with the same process components such as operational conditions, the scenario changing such points can be assumed and assessed. Second, the uncertainty in the life cycle of products, the decision rights of which belong to other organization, can be analyzed by changing the uncertain parameters.

The case example of first scenario development is shown as an exposure analysis by the installation of working shift into cleaning operation on the site represented as Case 2. **Table 4-26** organizes the analysis settings and results. The workplace concentrations of cleaning and other process are 9.83 $mg\cdot m^{-3}$ and 0.57 $\mu g\cdot m^{-3}$, respectively. The average concentration in Tokyo, Japan is 0.57 $\mu g\cdot m^{-3}$. Predicted daily intake (PDI [mg-intake·$(kg\cdot day)^{-1}$]) is a indicator of exposure to chemical utilizing for the calculation of impacts such as DALY. It is defined as the equation below.

$$PDI_i = \sum_j \left(C_j \cdot \Delta t_j\right) \cdot V_{inh} \Big/ \left(hr_{day} \cdot BW\right) \tag{4-12}$$

Table 4-26 Exposure analysis by the installation of working shift of cleaning (Agent: TCE)

Shift	1	2	5
N_{worker} of cleaning	2	4	10
N_{worker} of other process	20	18	12
Cleaning time [hr]	8	4	1.6
Individual PDI of worker of cleaning [$mg \cdot kg^{-1} \cdot day^{-1}$]	1.01E+00	5.04E-01	2.02E-01
Individual PDI of worker of other process [$mg \cdot (kg \cdot day)^{-1}$]	1.75E-04	1.75E-04	1.75E-04
MOE of worker of cleaning [-]	2.17E+01	4.33E+01	1.08E+02
Total PDI of worker [$mg \cdot (kg \cdot day)^{-1}$]	2.02E+00	2.02E+00	2.02E+00

where C_j is the concentration of chemical in case j [$mg \cdot m^{-3}$], Δt_j is the time duration of exposure to chemical at C_j [hr], V_{inh} is the average inhalation of human (20 $m^3 \cdot day^{-1}$), hr_{day} is the hours per day (24 $hr \cdot day^{-1}$), and BW is the average body weight (65 kg). PDI is dominated by the exposure concentration of chemicals. Cleaning operation has large potential of exposure to chemical in high concentration as shown in **Table 4-26**. If the number of workers engaging cleaning operation is increased, the working time for cleaning is reduced individually. Although the total PDI of all workers in a cleaning plant, five shifts working of cleaning can increase the MOE of each worker more than 100, which is the uncertainty factors (UF) of MOE. Because MOE more than UF means that the risk is sufficiently low, this change of work schedule can be an effective process improvement. Such detail exposure analysis can be fulfilled by plant-specific RA. Especially, MOE can be regarded as a meaningful indicator to judge whether an alternative is effective. As mentioned above, the scenario development and analysis can be effective for risk-based interpretation.

4.6.4. Conclusion

The way of interpreting evaluation results has two approaches, absolutely understanding the physical meanings of risk indices and indicators, and relatively comparing the results of alternative decisions. Both are available in risk-based decision making, and knowledge utilized in risk specification can be useful resources. Local risks visualized by RA should be judge whether they are acceptable, because such risk indices are sometimes critical for decision makers. On the other hand, global impact has often big uncertainty to understand quantitatively the physical meaning, because some impact categories are assumed that they occurs in several decades after emission. For such results, comparative decision making is applicable with optional methods for easy interpretation such as grouping, normalization, and weighting. This section presents the method of interpreting evaluated risk by associating the knowledge on risk indices and compromising techniques.

Chapter 5. Activity and Information System Modeling

5.1. Introduction

This chapter presents the activity and information system modeling representing the risk-based decision making, which is proposed in the last chapter, Chapter 4. As the benefits and requirements of modeling them were discussed in section 2.2, business and supporting system modeling are strongly needed to enhance the practicability of such decision.

IDEF0 and UML are applied in this chapter to develop required models. The section 5.2 introduces the developed business model of on-site engineers to design a practical process enabling reduction in risks. The business procedure is developed through the investigations on industry-specific conditions at metal cleaning. This business modeling relating actual activities with knowledge on process design and evaluation enables the conversion of knowledge represented as logically scientific techniques in Chapter 4 into practical one in business. Even if the knowledge become practical, actual decision-makers may have difficulties to perform defined activities appropriately. Based on the developed model, the obstacles inactivating proposed risk-based decision making in practice are specified. To overpass three obstacles, supporting mechanisms are necessitated as software information system activating the knowledge in business. The system requirements are defined by utilizing IDEF1x (Entity-Relation diagram), UML use case, activity and sequence diagrams. In addition, with regard to EvM tool, a prototype tool has been developed on the required GUI. IDEF0, IDEF1x models and UML diagrams are developed by KBSI tools (AIØ WIN 8.0 and Smart ER 5.0) (KBSI 2001, 2006) and Pattern Weaver version 2.2 (Technologic Arts Inc. 2007) on Eclipse SDK 3.1.1 (Eclipse Foundation 2005) for Java development environment, respectively.

5.2. Risk-Based Decision in Business Model

5.2.1. Conversion of Structured Knowledge into Practical

The Top Activity A0: Decide a Measure to Reduce Chemical Risks Originating from Operated Process

Figure 5-1 shows the top activity of the developed IDEF0 model for risk-based decision making. The goal of this activity is to obtain a reduction measure of chemical risks attributable to process in use. The viewpoint is defined as on-site engineers who are well-versed in targeted process. The activity model can demonstrate the actual procedure of risk reduction considering individual constraints and available information by the engineers. It can be applicable in all types of industrial processes by preparing required plant-specific information.

Existing constraints on process design could be mainly divided into three types of group on their variability: general, plant-specific and project-specific ones. Related regulations and climate conditions are generally fixed conditions for decision-makers on all sites, and thus, they can be called general conditions. Plant-specific conditions are latent ones and cannot be changed on site, for example, ambient surroundings, products and process functions. Project-specific conditions, that are budget and desired value of risk reductions, can be redefined by someone in site, although they may not be modifiable for the decision-maker of process design. If any alternatives could not achieve given desired value of risk reduction or an additional investment exceeding given budget would be required, such information is outputted to higher decision-makers. According to this need, the viewpoint of this activity can request the modification of project-specific constraints to the upper decision-makers.

A0 Layer: Overview of the Risk-Based Decision Making

Figure 5-2 shows the sub-activities of risk-based decision making. In A1: manage decision of alternative process, external controls should be interpreted and transformed into convenient styles, e. g., quantitative values for evaluation activities, because some external controls are quite abstract for practical procedures. Based on the quantified controls, process in use is assessed in A2: evaluate process in use. This activity includes the main procedures of integrated application of different assessment methodologies. To reduce the evaluated risk, A3: generate alternative candidates generates alternative candidate processes using technical information. A4: evaluate alternative candidates assesses the generated alternatives according to the way how process in use is assessed. Although the basic framework in activity A4 is the same as that in activity A2, data acquisition is different for the process in the middle of design. It requires mechanisms to estimate process data. Finally in activity A5: decide alternative process, an alternative process is decided on the basis of analysis and interpretation of all evaluation results. The differentiated interpretations are performed for the results of environmental impacts and local risks.

Internal constraint outputted from activity A1 becomes a common constraint to the other activities, because it includes converted external constraints. Although the names of control concepts of the activities A2-5 in Figure 3 are same, the contents of them are totally different for each activity. For example, internal constraint on evaluation activities (activities A2 and A4) includes the plant-specific environment for evaluating local risks, while one on alternative generation (activity A3) has the requirements for process functions. At alternative generation activity (activity A3), as well as such internal constraints, evaluation results of process in use are the control of activity. All evaluation policies and results become the controls of activity A5, where final decision will be made. If there are any feedback information including the requirements for more detail evaluations and further improvement of alternative candidates, they are returned from activity A5 to activity A1, and then, internal constraints are updated to reflect the feedbacks.

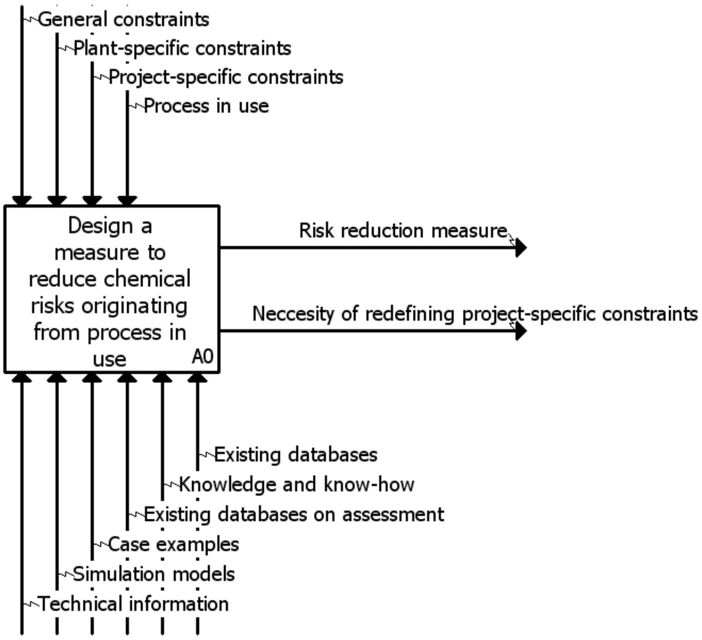


Figure 5-1 Description of the top activity

A0: *design a measure to reduce chemical risks originating from operated process*

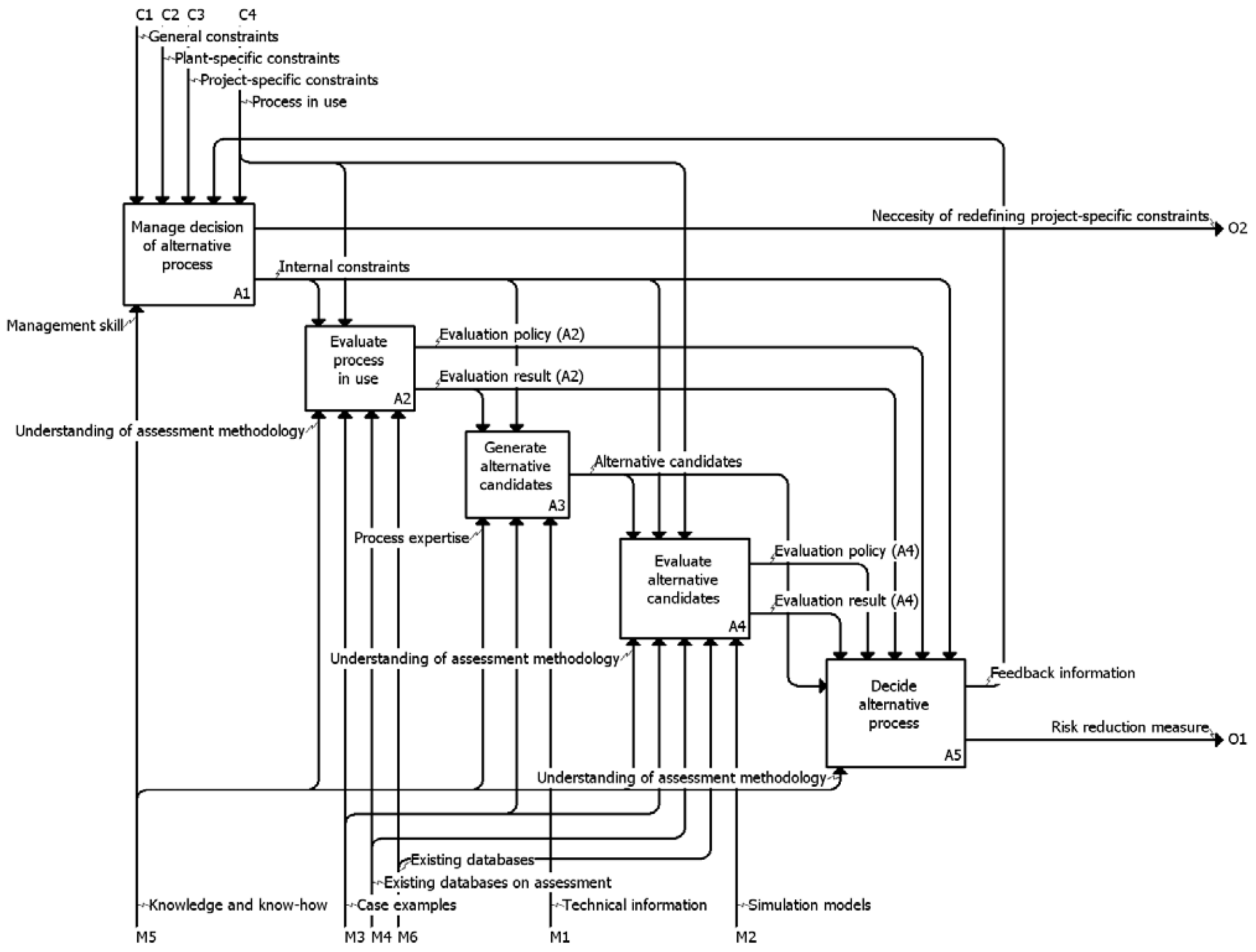


Figure 5-2 Overview of the proposed procedure for risk-based decision making. Activities A1-A5 are the sub-activity of activity A0

Evaluation Layer (A2: Evaluate Process in Use, A4: Evaluate Alternative Candidates)

Figure 5-3 shows the sub-activities of activity A2 in Figure 3 where different assessment methodologies are integrated for common constraints. Evaluation activities consist of three main steps: objective and settings, evaluation execution and data collection. Activity A4 has the same structure of activities. Additionally, interpretation of results is also one of the activities and located in activities A3 and A5.

Figure 5-4 shows the integrated evaluation phases of LCA and RA converted from **Figure 3-10**. Integration of assessment methodologies is achieved by combined objectives settings, comprehensive interpretation, and information share during a phase in both assessments.

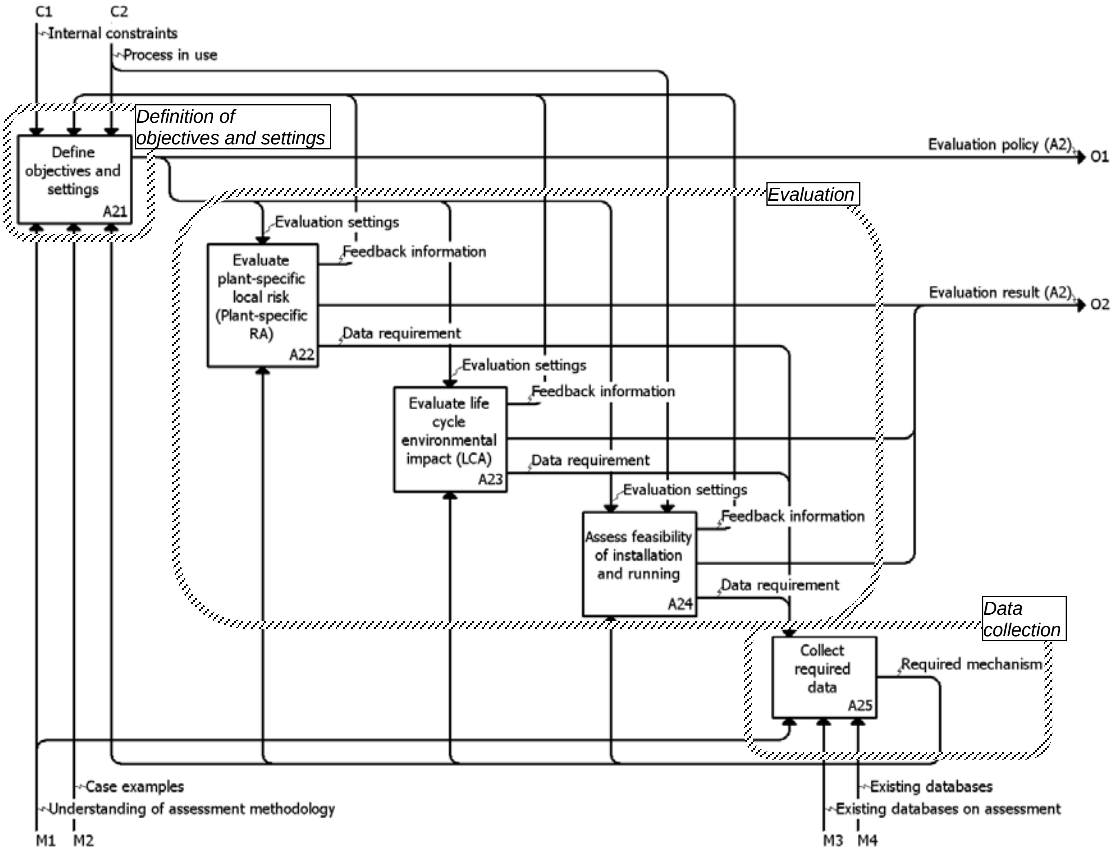


Figure 5-3 Description of the sub-activities of A2: *evaluate existing process*. Activities A21-A25 are the sub-activity of activity A2

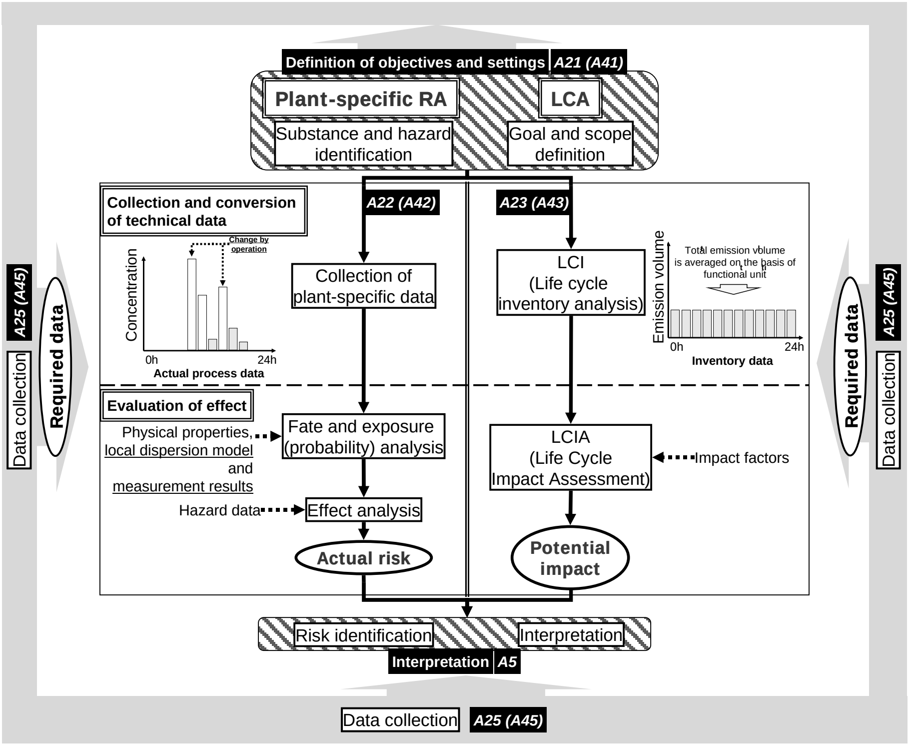


Figure 5-4 Integrated evaluation phases of LCA and RA with data requirements

In objective settings and interpretation, the activities stay in close contact to share information for the avoidance of inadequate settings of redundant evaluation indices and ineffective interpretation on a narrow field of vision. Comprehensive interpretation needs the judgment of reducing candidates and deciding an alternative under evaluation results considering the difference of their meanings. The key points of the integration of LCA and RA are the assignment of evaluation indices to each methodology considering the matching of the features of evaluation indicators and actual adverse effects, and the appropriate screening with sufficient understanding of results. These are accomplished by the developed activity models. In the following, each activity is explained along with the procedure shown in **Figure 5-4**.

Objective Settings

Activity A211 (activity A411) in **Figure 5-5** is the common step to analyze the assessed process for a fruitful definition of assessment conditions. Evaluations of risks are appropriately assigned to each assessment methodology to correspond with process situations and constraints from activity A1. Based on the process analysis and assignments, the evaluation settings are defined for RA, LCA and installation feasibility assessments. The activities for goal and scope definition of LCA are activity A212 (activity A412) and its subactivities. In these activities, functional unit, system boundary and impact category are defined. The substances to be dealt with are set and hazardous properties to be attended are specified in activity A213 (activity A413) and its subactivities for plant-specific RA.

In all activities in the phase of objective settings, the internal constraints and process information are the dominant factors to feature the output "evaluation policy". Thus, this phase is an important to reflect the constraints in evaluating, and then, risk reduction measure. In this regard, according to the progress conditions of each assessment, they can be back to this phase and all settings of constraints can be redefined as more detail one on the basis of the feedback information.

Collection and Conversion of Technical Data

Based on the evaluation policy outputted from activity A21 (activity A41), RA, LCA and installation feasibility assessments are executed simultaneously. Separated from the main activities of these assessments, data collection is defined to share the information among them. The evaluation policy causes technical data requirements inputted into activity A25 (activity A45) where required resources are collected under the limitation of available resources for a decision-maker. In order to calculate plant-specific local risks, temporally and spatially-detailed information must be acquired on the operation and microenvironment inside and outside of a site. Such information varies greatly from plant to plant, i.e., plant-specific information. This is the raw process data on the input/output or the situation of site without any conversion. In LCA, by the assumption of being temporally and spatially-equalized data, life cycle inventory analysis can output the total emission amounts through a life cycle. The inventory of the process of decision makers can be obtained by converting raw process data on functional unit. Released LCA-databases and software (Pré 2006; Swiss Center for Life Cycle Inventories 2008; JEMAI 2005; JLCA 2008) can be applied as inventory data acquisitions in the other life cycle processes of decision makers. Note that in the sub-activities of activity A4, simulation model and alternative candidate processes are added as mechanisms and constraints, respectively.

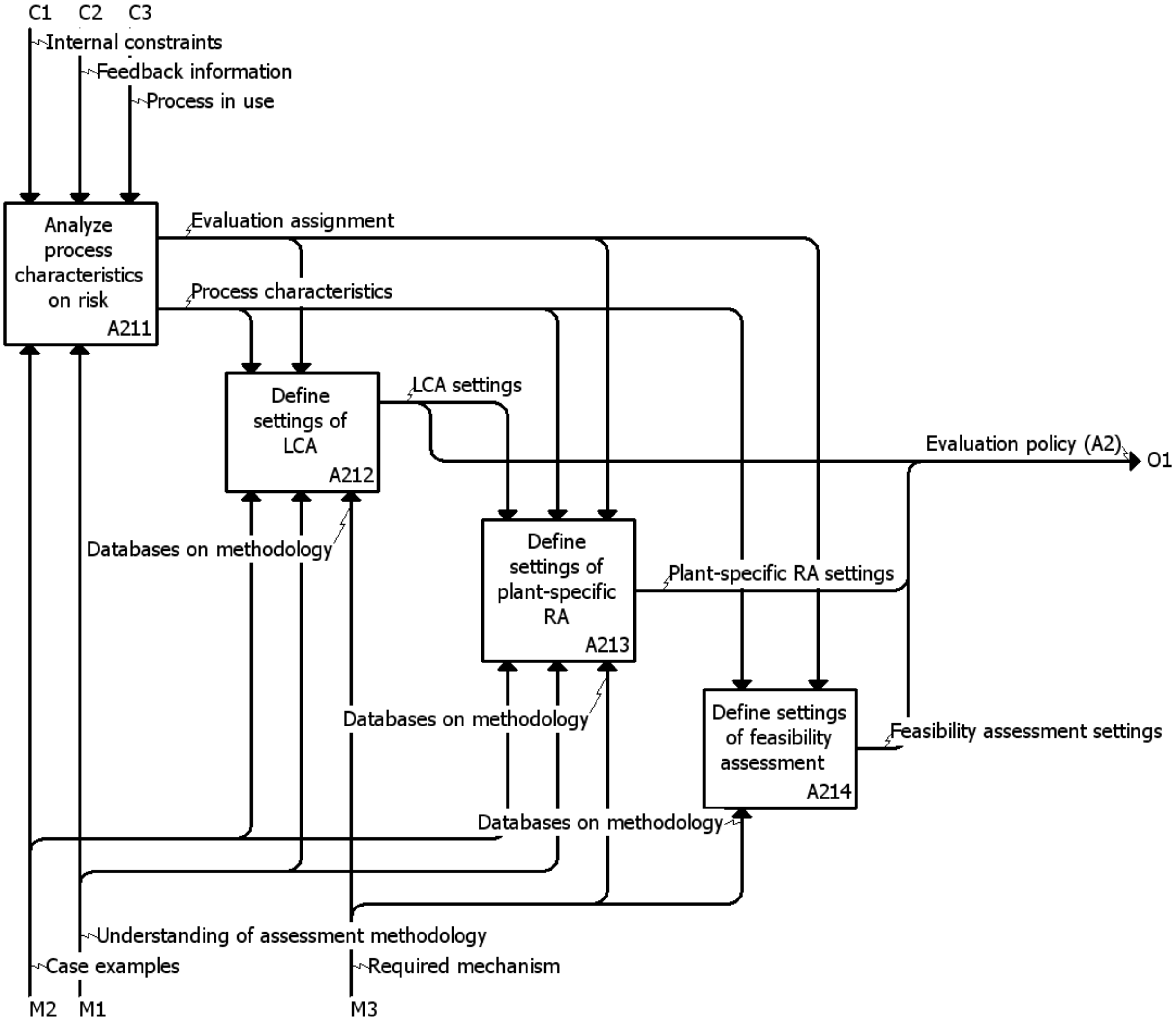


Figure 5-5 Description of the sub-activities of A21: *perform objective settings*. Activities A211-A214 are the sub-activity of activity A21

Evaluation of Effect

This phase also needs resources from activity A25 (activity A45), and they are requested as data requirements for the activity. In RA, real situation on site can be taken into account possibly by utilizing physical conditions on site, measured process data and available local dispersion models (METI 2005a; US-EPA 2004). Based on fate and exposure analyses, hazard values such as no-observed-adverse-effect level (NOAEL) of substances are applied as scientifically and generally objective criteria of local risks, where existing results and databases (Nakanishi 2005; Kajiwara 2008; CIS 2007) can be referred. On the other hand, in LCA, potential impact is evaluated by multiplying LCI results and impact factors (Pré 2001; JLCA 2008; Itsubo 2003; Research Center for Life Cycle Assessment 2007) at LCIA. Most impact factors are developed on emitted substances under several assumptions of the substances and situations, for example, chemicals are emitted somewhere in a specific area with an average population. The impact factors become coefficients to evaluate the average of damage on the targeted impacts in a specific area and long-term effect by expanding the time span of fate analysis.

Interpretation

Evaluation results should be interpreted for alternative generation and decision making in activities A3 and A5 with sufficient attention given to the difference between evaluation methods and indicators. Temporal aspects are mainly associated with the temporal profiles of technical data and fate analysis, and spatial aspects are associated with the assumption of evaluation of effect.

Figure 5-6 shows the sub-activities of activity A5 where the evaluation results are interpreted. Through the activities in this layer, the evaluation results are comprehensively interpreted. The importance is the existence of the screening activity followed by comparative selection phase.

According to the phases of technical data collection and effect evaluation shown in **Figure 5-4**, RA can apply temporally and spatially detailed information more easily than LCA. This means that the evaluation results of RA indicate actual risks which should be judged whether acceptable or not, individually. The acceptable levels of each index should be defined on both objective and subjective criteria of decision makers, because they can take into account the actual constraints appropriately. For the remained alternative candidates, comparative selection is carried out in activity A54. Although this selection is quite simple, i.e., less adverse effects will be better. Some cases may cause trade-off relationship in several indices. For such cases, optional formatting techniques, such as weighting, can be applicable in activity A53 before activity A54.

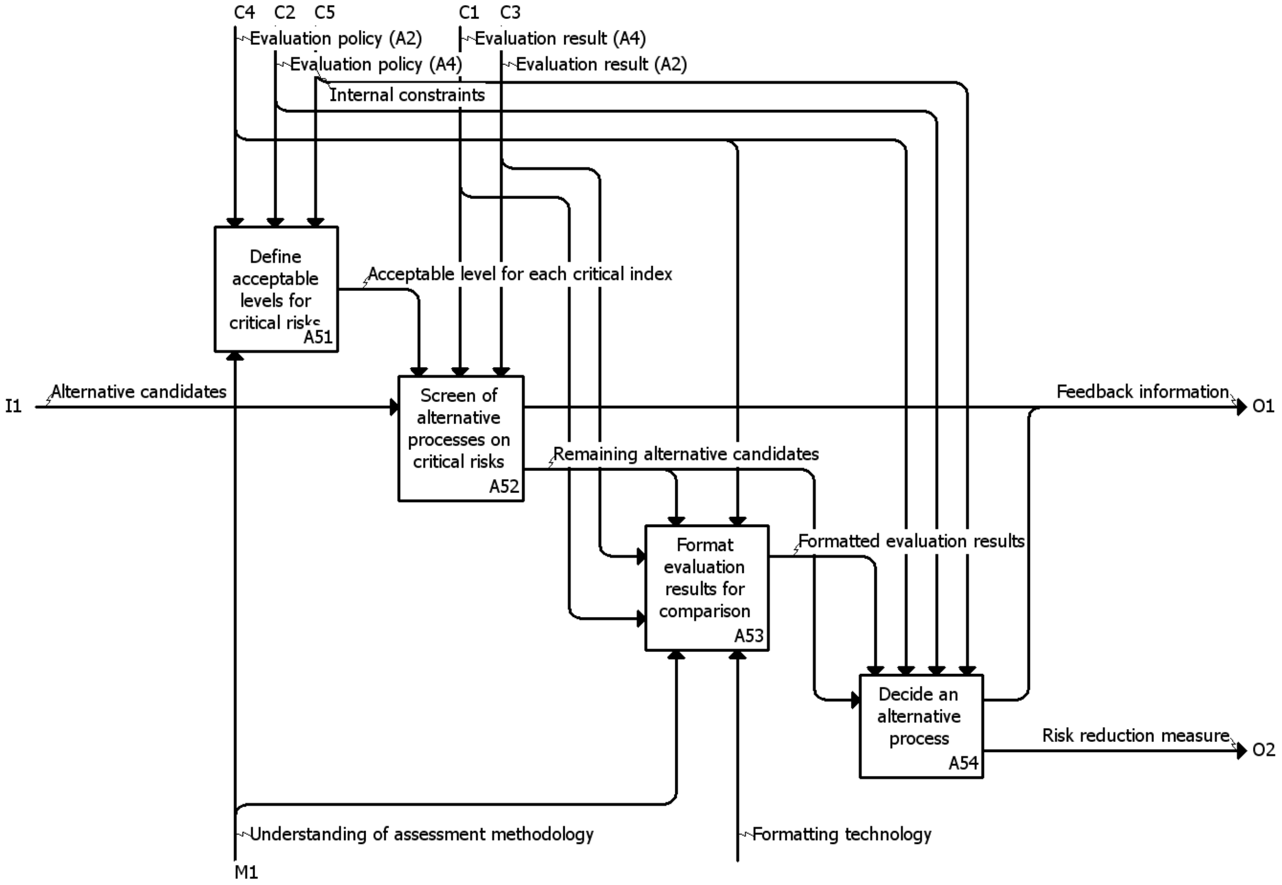


Figure 5-6 Description of the sub-activities of A5: *decide alternative process*. Activities A51-A54 are the sub-activity of activity A5

An alternative process will be decided, if it meets the reduction target and achieves installation feasibility. Installation feasibility assessments is performed at activity A24 (activity A44), where the feasibilities of a process on running and installation are analyzed. Several aspects are taken into account as a key factor of decision making; effect on process function, economic feasibility, installation location and construction. In this time, the cost requirements can be regarded as the investments to reduce risk. It means low cost is not always a strong decision factor. Such interpretation is included in the activity A5. If necessary, additional costs should be accepted for a sufficient reduction in risks. In such cases, feedback information will be generated and become a new constraint for further improvements of process or budget.

Summary of Business Modeling

The development of IDEF0 activity model could visualize the complicated activities and information flows required for the actual implementation of assessment methodologies into decision-making. Based on the activity model, the procedures for practical integration of methodologies can be shared between on-site engineers and researchers.

Visualization of activities with information flows enables the productive discussions on actual procedures of decision-makers and information infrastructures to be maintained by researchers and other stakeholders. This can be an essence for propagations and implementations of various assessment methodologies such as LCA and RA into practice in industries and government. As well as the developments of novel assessment methodologies, activity modeling of actual procedures for decision-makers should be discussed for quick and accurate implementation of scientific methods on industrial ecology. By mapping and converting EvM on actual business model, the structured knowledge of LCA and RA became a practical style of knowledge.

As well as EvM, other knowledge on process design and evaluation were connected with actual business model as shown in **Figure 5-7**. The design procedure of cleaning process is illustrate in **Figure 5-8**as a flow chart.

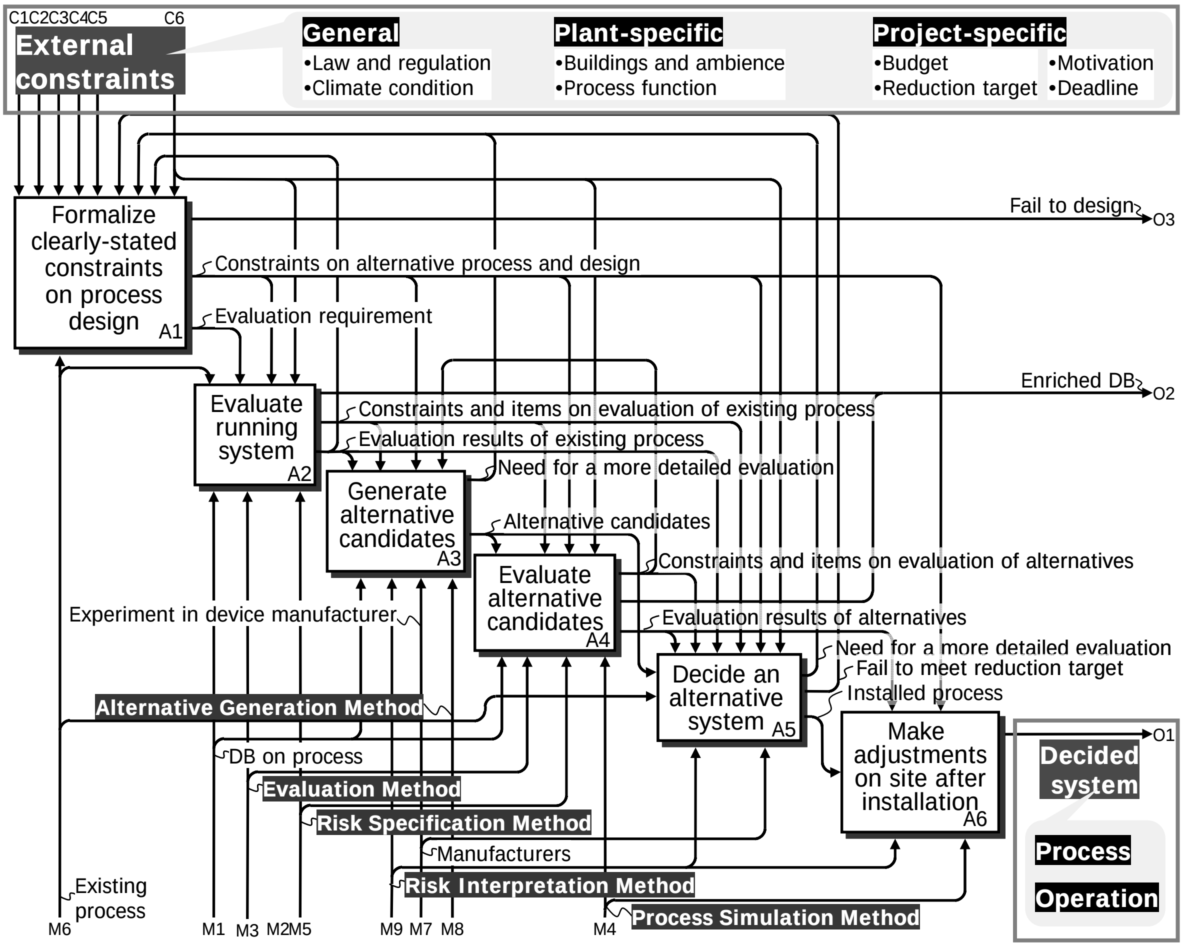


Figure 5-7 Business activities with five supporting methods

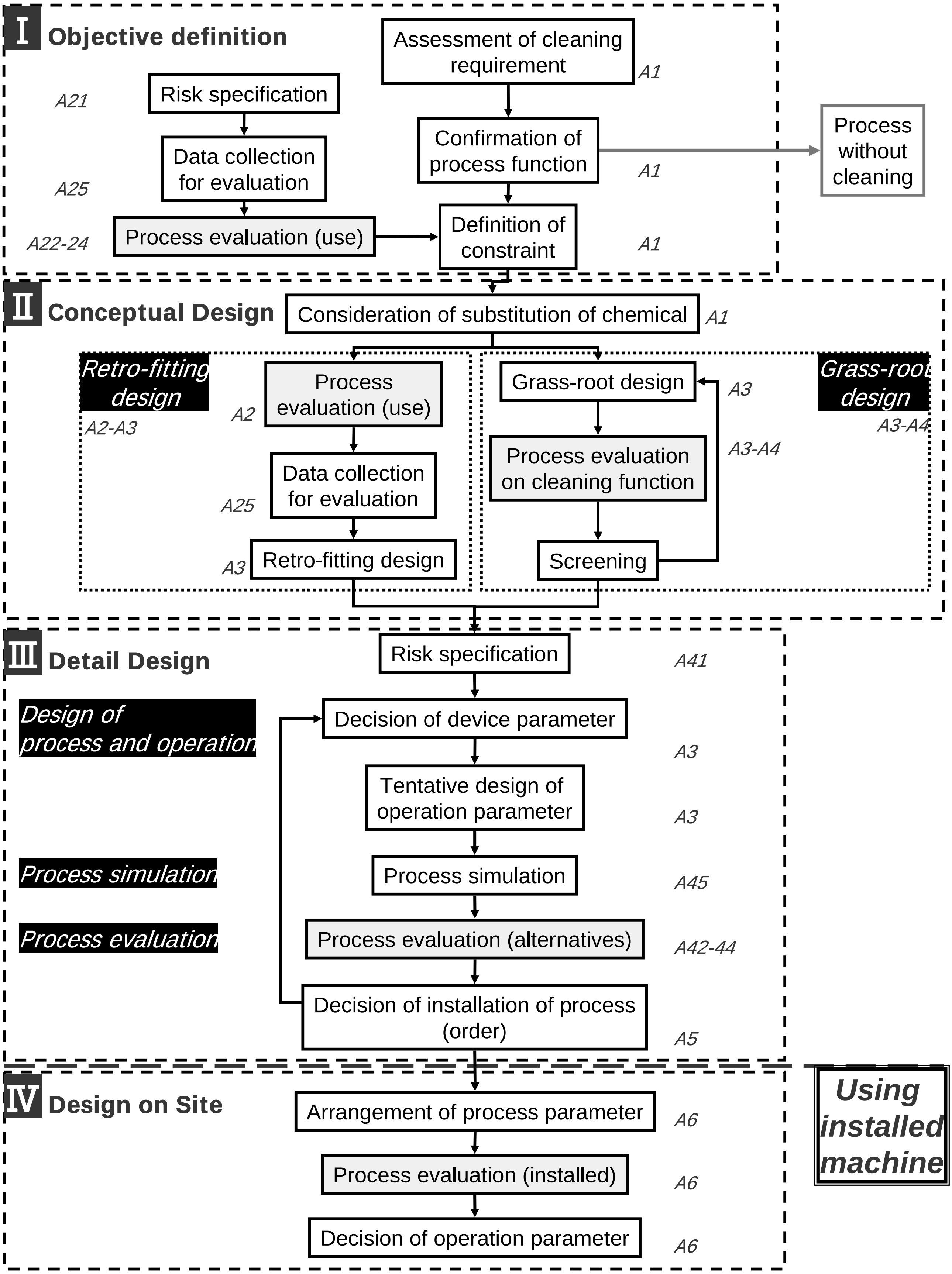


Figure 5-8 Procedure of proposed industrial cleaning process design

5.2.2. Obstacles Inactivating Risk-Based Decision Making

Analyzing the developed model with actual situation demands in cleaning sites, the obstacles inactivating risk-based decision making in practice were specified. In this analysis, it is considered in a strict sense that the activities included in the developed IDEF0 model are what researchers assumed that the viewpoint of activities, who is the actual decision maker on site, could execute. It means that the implicitly utilized knowledge of researchers might be overlooked, for example, the understanding of assessment methodologies. In this analysis, such so-called *general knowledge as researchers*, which is not common for on-site engineers, is carefully considered.

Nonexistence of Suitable Mechanisms

Mechanisms required for the proposed risk-based decision making need a lot of available knowledge in an integrated structure. Activities utilizing RSM and AGM are ones requiring such highly structured knowledge, which are the integrated scientific knowledge on risk indices and indicators, and that on available engineering technologies and their relationship with evaluation results. To cover the nonexistence of suitable mechanisms, available information models should be defined and related with the objectives of activities utilizing RSM and AGM.

Low Practicability of Activities with Existing Mechanisms

In the activities on LCA, for example, existing software tools can be applied to achieve the evaluation objectives. In this regard, however, it depends on the background knowledge of actual decision makers. There are possibilities that the viewpoint cannot fully utilize such existing tools for their process improvements. Customized tools must be strongly needed to enhance the practicability of scientific assessment technologies such as LCA and RA. As well as the scientific gaps between researchers and actual decision makers, the actual needs of them should be addressed. The objectives of LCA and RA tools are the evaluation and execution of these assessments. Whereas, the actual needs of industrial decision making are to take actions based on evaluation results, especially in process design, for process improvements. Such needs should be met by appropriate supporting mechanisms.

Hard-Cooperative Mechanisms

Lots of knowledge and technologies have been developed in each field and sectors for solving single problem and all of them are needed. RSM and EvM are based on researches on scientific assessments such as LCA and RA, AGM should be from the case-specific industrial sectors, such as JICC, PSM can become functional tools by deriving from physicochemical and statistical analyses at the viewpoints of practical engineering, and RIM should include various interpretation heuristics. For the integrated risk-based decision making, these resources should be able to cooperate in a decision making on the basis of not only logically, but also software information system. It means that the mechanisms for a business model should be available as a system interconnecting the knowledge on process design and evaluation, which is separated in **Figure 5-7**

5.2.3. Activity Modeling with Suppot by Information System

Activity Analysis, Decomposition, and Redefinition

The activities represented in **Figure 5-7** include the required ones for the proposed methods in Chapter 4. It means that the overview should perform each activity by collecting information and other technologies. In this regard, however, it depends on the knowledge, viewpoint can utilize implicitly. The difference of fundamental knowledge on process evaluation and design has possibilities to make changes in the results of decision making.

An easy example can be demonstrated on the calculation in process evaluation. **Figure 5-9** shows an activity to assess a process by LCA using Microsoft Excel®. All required data can be available as input to the activity. This activity is very easy for the researchers and practitioners on LCA. For the beginners of LCA, however, this activity needs the study of LCA before performing. Moreover, for the beginners of Excel, the calculation in LCI is completely difficult to perform by hand. These gaps of skills and knowledge on mechanisms might result in the failure of the activity. For the activity in **Figure 5-9**, the hidden mechanisms, which are generally accessible for researchers, might be the knowledge and technique on LCA and Excel. At the same time, the understandings of researchers on LCA may also be hidden in **Figure 5-9**, being the rule of LCA. Such implicit and basic knowledge among researchers should be carefully considered for business modeling.

Figure 5-10 shows activity analysis, decomposition, and redefinition for enhancing the practicability of risk-based decision making. In the analysis, the activities, which are difficult for actual decision maker to perform, are specified and retrieved from the activity model. This is the decomposition of no-practicable activities. Remained activities, which are practicable for decision makers, are redefined as a business model for them. Retrieved activities become ones of support mechanisms. This steps can convert the activities of researchers into practicable ones for actual decision makers. At the same time, the conceptual requirements of support mechanisms can be indicated.

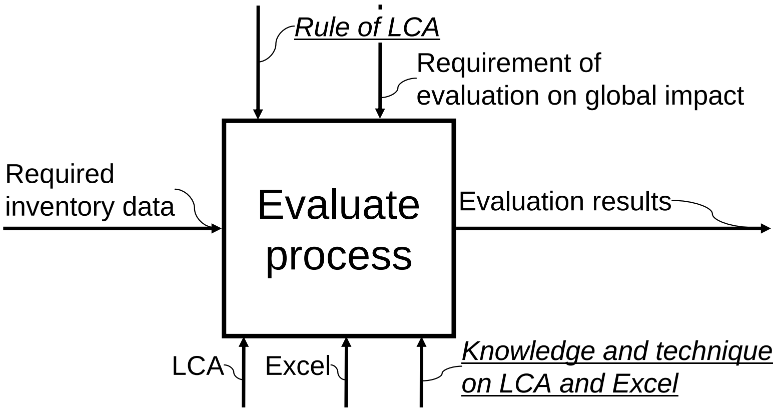


Figure 5-9 Example of problem in the gaps of skill and knowledge on mechanism at process evaluation

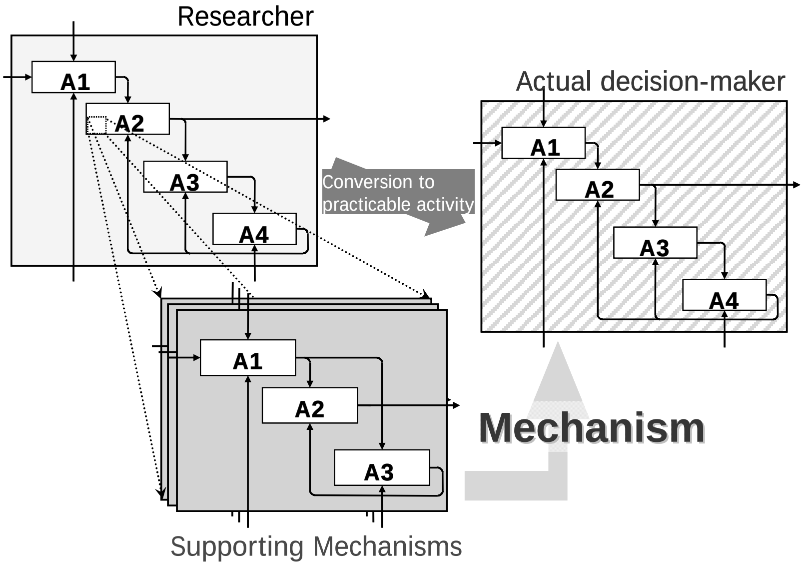


Figure 5-10 Activity analysis, decomposition, and redefinition for enhancing the practicability of risk-based decision making

System Implementing Cooperative Supporting Mechanisms

Figure 5-11 shows the conceptual use case of proposed supporting mechanisms. Each mechanism has each role for risk-based decision making. An integrated GUI can play the role organize the all activities and information by the mechanisms. The GUI activate the data transferring among mechanisms as shown in **Figure 5-12**. Based on the transferred data and user inputs, the supporting mechanisms perform the assigned activities. The overview of activities relationship among all mechanisms and users is visualized in **Figure 5-13**.

The core algorithm of the required system should not be dependent on industries and decision makers. The interaction between system and users should be specific for situation demands. It is regarded as the difference of the degree of the activation of knowledge by supporting system. For a researcher who has well-understandings on scientific methods, the system does not have to activate such knowledge largely. On the other hand, a supporting system should be able to activate knowledge significantly, which means that the system can execute most of the procedures in risk-based decision making with the inevitable activities by decision makers, especially on-site engineers in SMEs.

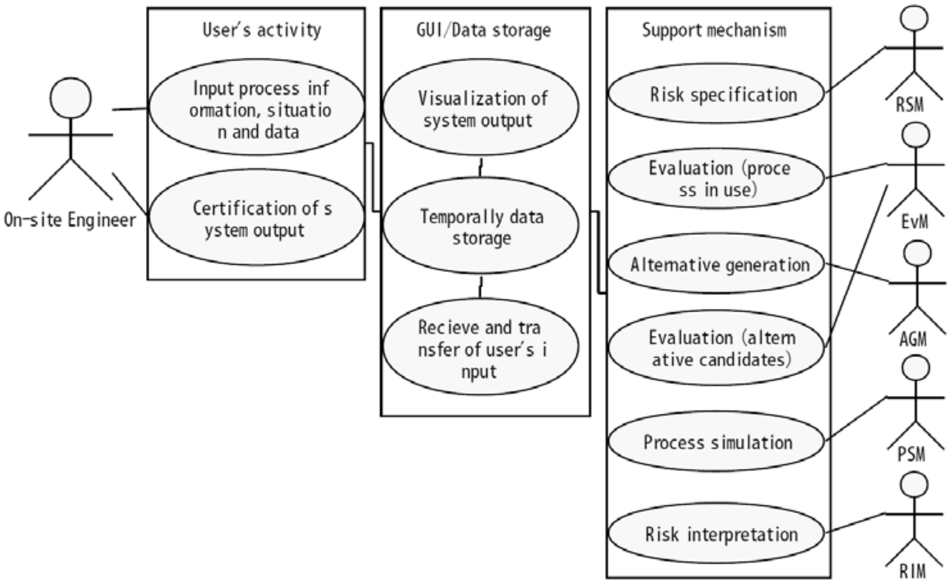
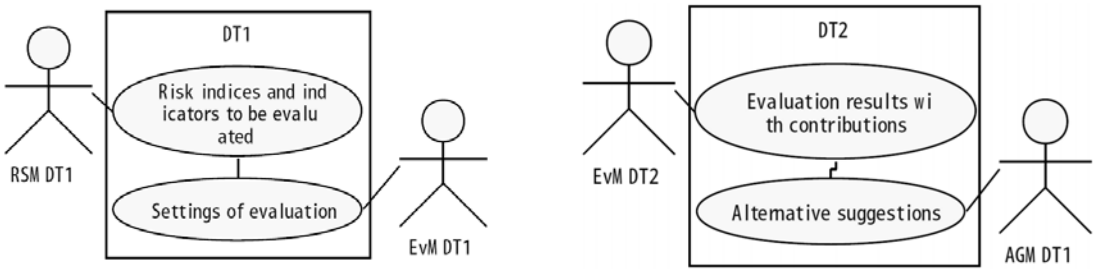
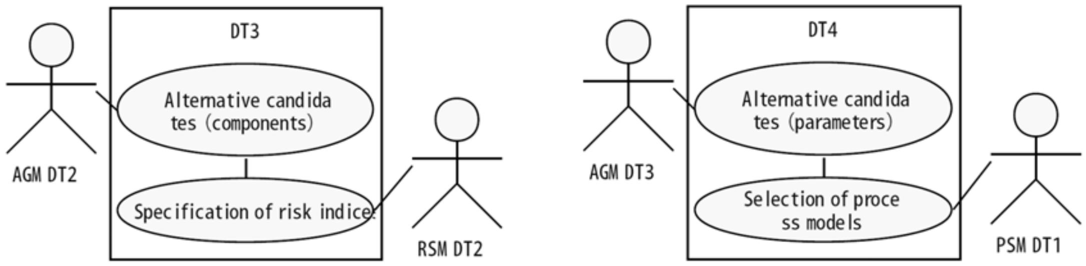


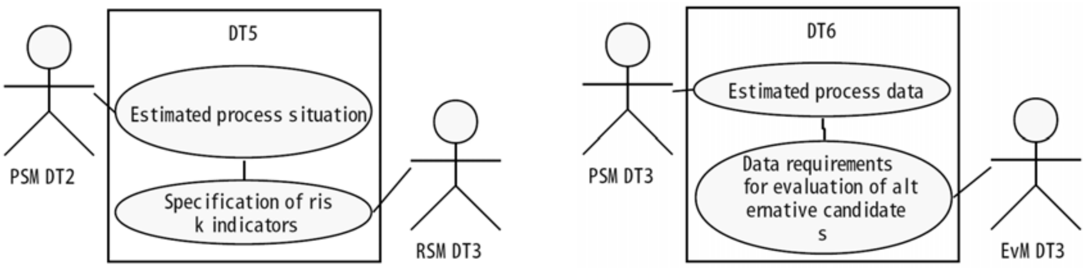
Figure 5-11 Conceptual use case of proposed mechanisms



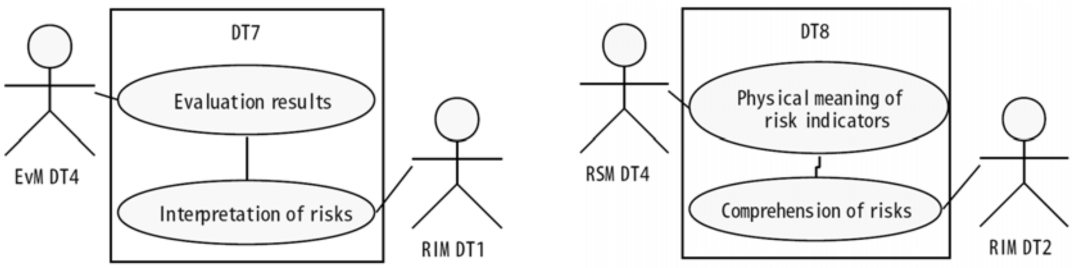
(a) RSM/EvM (b) EvM/AGM



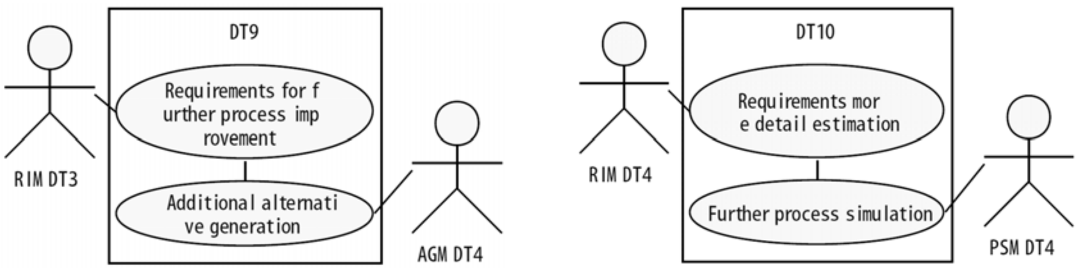
(c) AGM/RSM (d) AGM/PSM



(e) PSM/RSM (f) PSM/EvM



(g) EvM/RIM (h) RSM/RIM



(i) RIM/AGM (j) RIM/PSM

Figure 5-12 Conceptual use case representing data transfer among supporting mechanisms

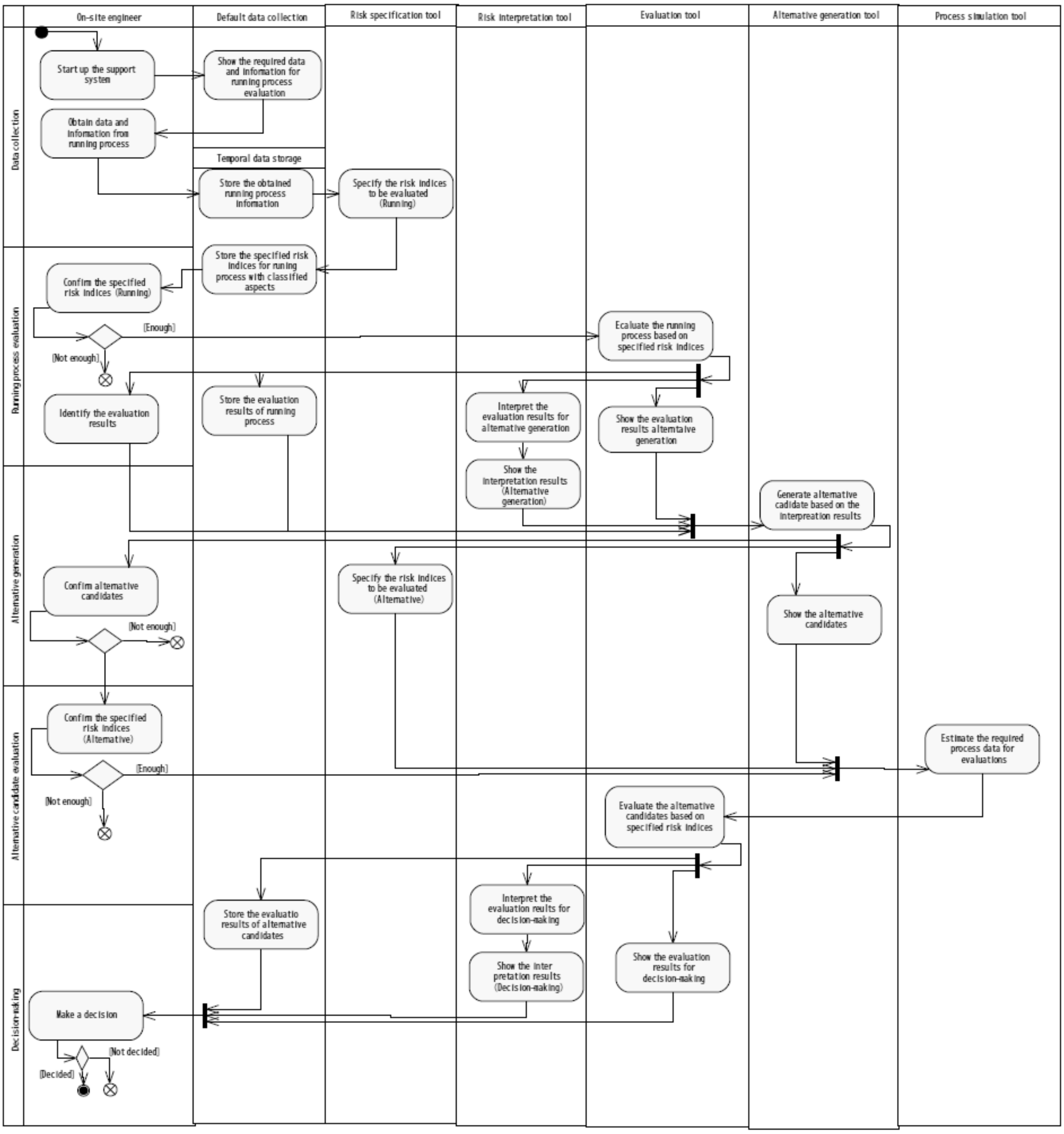


Figure 5-13 Activity relationship among proposed mechanisms (UML activity diagram)

5.3. System Modeling for Activating Knowledge

5.3.1. Activation of Process Evaluation

Needs of Mechanism

The execution of process evaluation based on LCA and RA requires technical knowledge and skills on them. The evaluation results have possibilities to be changed considerably with the settings of assessments, and then, they can change final decision. Appropriate process evaluation must be essential for risk-based decision making.

Although software tools for scientific assessments have already been developed (Pré 2006; JEMAI 2005), they need somewhat specialized knowledge, skills, and experiences on the assessments. This means that the decision maker without any knowledge on assessments have great difficulties to utilize fully such tools for decision making. Customized tools for each industrial sector and decision maker should be available. On the other hand, from the viewpoint of familiarizing such scientific methodologies and educating industrial decision makers, the customization should not be too much to understand the meanings of evaluation results. Adequate adjustment of customization should be discussed along with the needs and objectives.

User Requirements Definition

For activating the discussion on the customization of tools for decision maker, the UML modeling can be one of the effective measures. **Figure 5-14** shows the conceptual use case of the mechanism for EvM. The on-site engineers need to input process inventory and information to have the mechanism evaluate process. More detail use cases on the evaluations of process in use and alternative candidate processes are visualized in **Figure 5-15** and **Figure 5-16**.

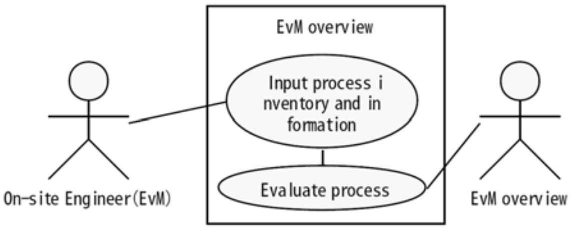


Figure 5-14 Conceptual use case of the mechanism for EvM (UML use case diagram)

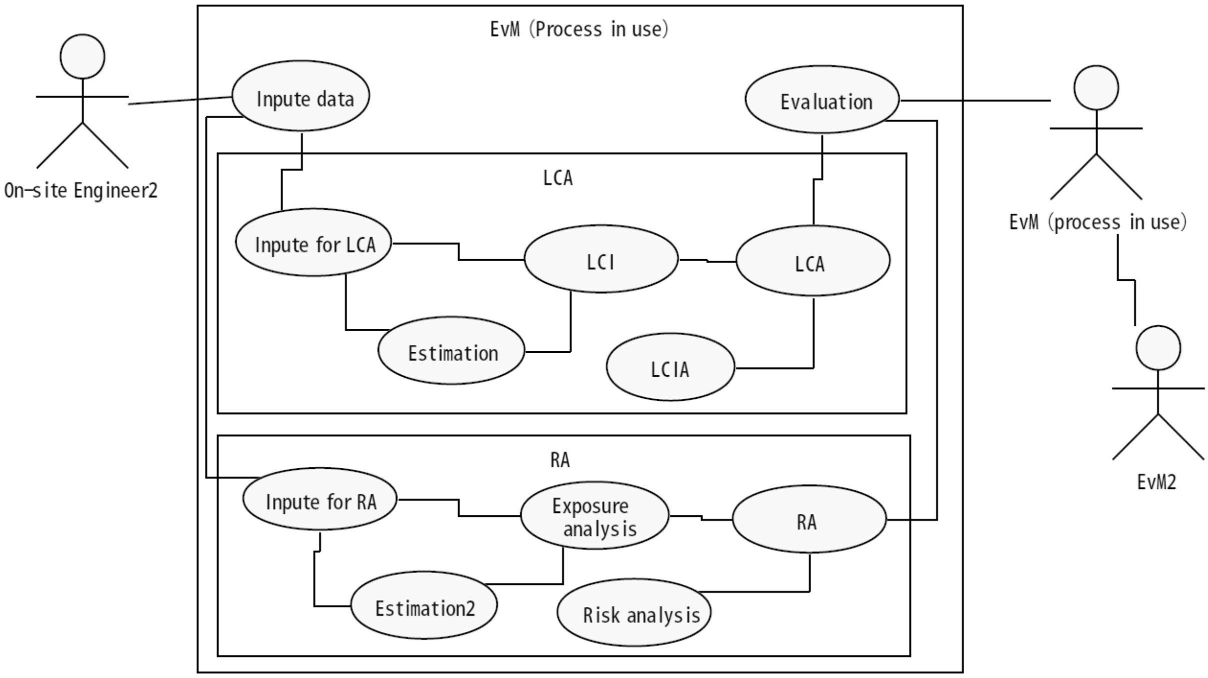


Figure 5-15 Detail use case in evaluation of process in use by the mechanism for EvM (UML use case diagram)

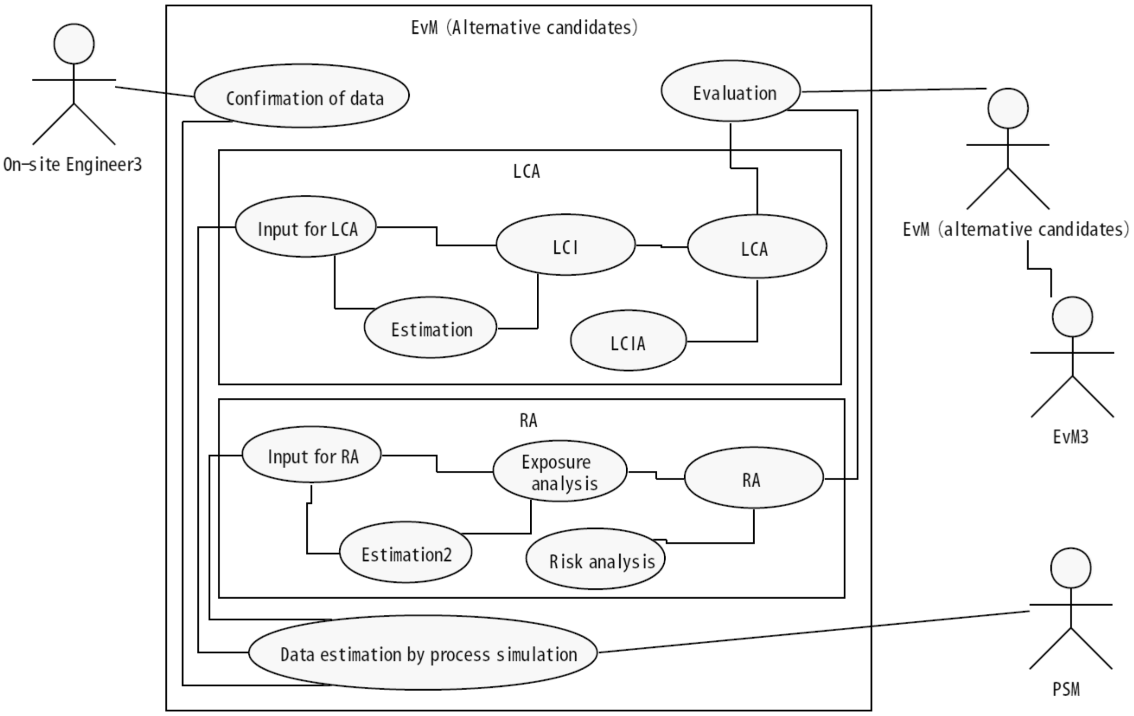


Figure 5-16 Detail use case in evaluation of alternative candidate processes by the mechanism for EvM (UML use case diagram)

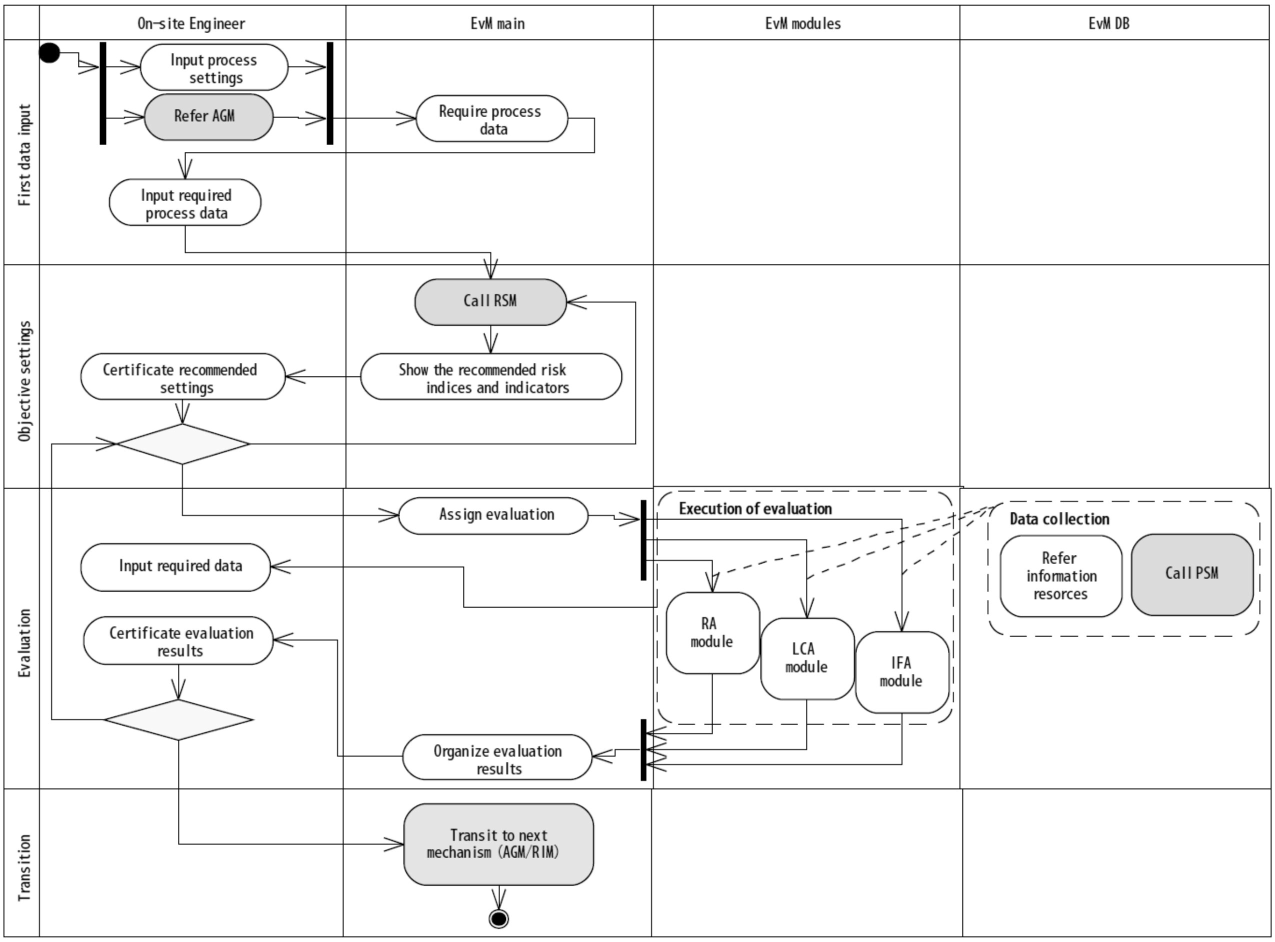


Figure 5-17 Activity relationship in the mechanism for EvM among system user and system modules (UML activity diagram)

The difference of the activity included in the evaluations of process in use and alternative candidates is mainly regarded as the acquisition of process data required for LCA and RA. In the use case of the evaluation of alternative candidate, PSM has a connection with the activity of EvM. **Figure 5-17** shows the activity relationship in the mechanism for EvM. Three call activities have important roles to facilitate each evaluation phase. In the first data input phase, EvM should take into account the alternative process settings, which requires the connections with AGM. Similarly, the objective settings and evaluation phases requires the connections with RSM and PSM, respectively.

System/Data Requirements Definition

The proposed mechanism for EvM is divided into several parts to fulfill the roles represented in **Figure 5-17**. In such modules, GUI is one of the most important modules for the integration of assessment methodologies. **Figure 5-18** is the sequence of the GUI of the mechanism for EvM modeled as a UML sequence diagram. This GUI is the interface among different assessments by controlling objective settings and assignments with RSM, transferring information from AGM and PSM, and sharing data by storing it. Therefore, this GUI can be called as "information management module". From this module, the activation is moved to each module for assessment.

The required information for each assessment is organized in **Table 5-1**, and they are collected by the common GUI. In this regard, however, there is a lot of missing information by a just collection directly. Estimation of missing information is available in the mechanism for EvM as shown in **Figure 5-19**.

Table 5-2 organizes information required for the specification of the consumptions of electricity and fuel/steam on cleaning process in the mechanism for EvM. Such estimation is inevitable in the actual calculation of LCA and RA by utilizing raw process data.

Figure 5-20 shows the sequence of the main LCA module on cleaning process in the mechanism for EvM. The settings required for LCA such as system boundary and functional unit are predefined and cumulated in the mechanism as default settings. The activities of users are just certifications of such default settings and input of their own process inventory. Although the life cycle inventories are analyzed in the mechanism, there is missing information for the calculation as discussed above. At that time, the activation moves to estimation modules. **Figure 5-21** shows the sequence of the estimation of utility use at a cleaning process as an example. In this estimation, the available actual data is fully utilized to reduce the uncertainty of LCA results. At the end of the sequence, the mechanism transfers all results to the mechanism for AGM/RIM, after the calculation of all LCIA results including characterization, damage, and integration into an indicator.

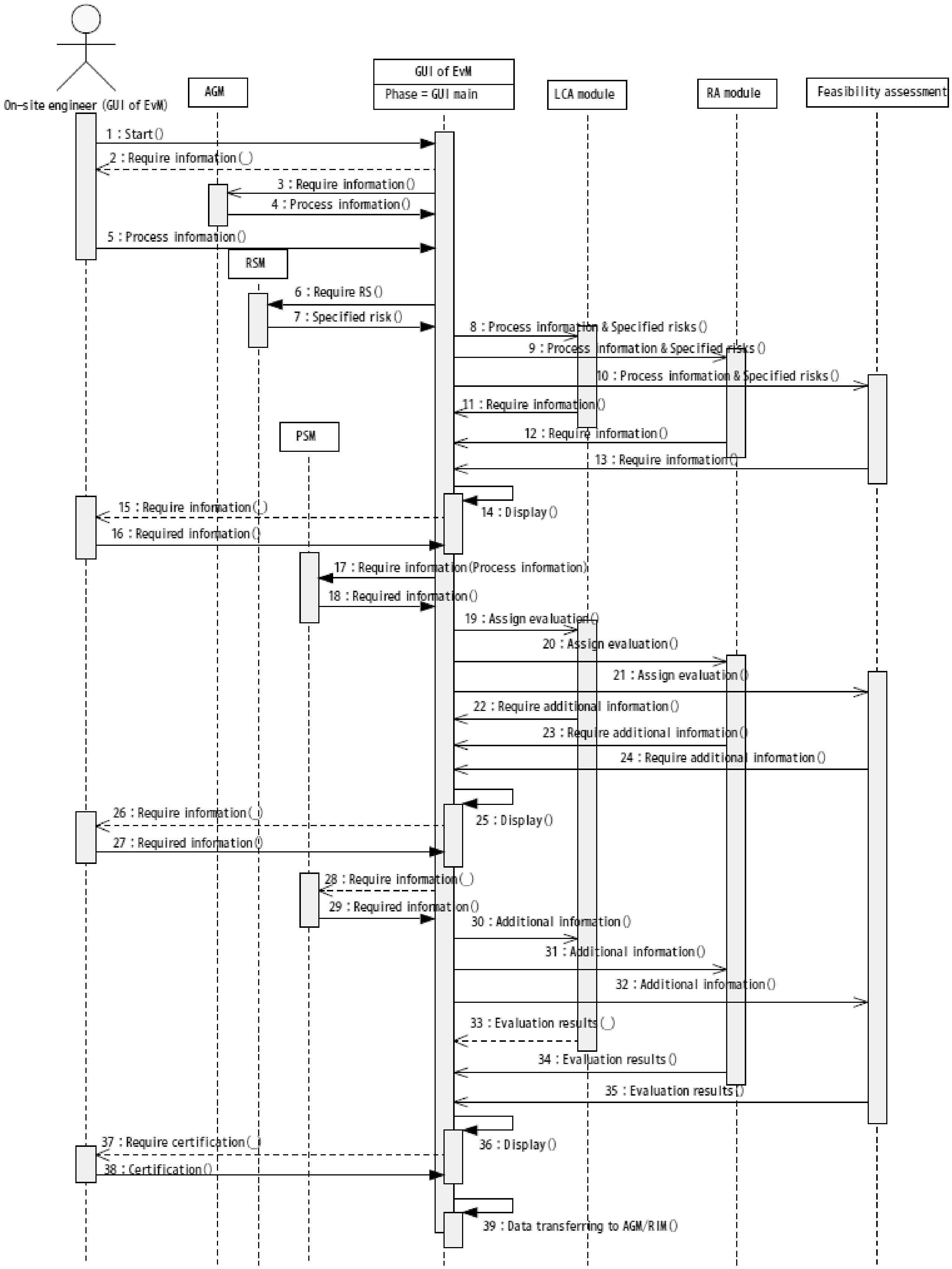


Figure 5-18 Sequence of the GUI of the mechanism for EvM (UML sequence diagram)

Table 5-1 Required data for LCA and RA

LCA	
Main reference flow for FU	Unit example
Throughput weight	kg
Throughput number	-
Cleaned area	kg
Removed impurity	kg
Working time	hr
Working day	$day \cdot month^{-1}$
Reference flow (per FU)	Unit example
Cleansing agent use	kg
Activated carbon use	kg
Electricity use	kWh
Steam	MJ
Fuel	MJ
Water	L
The other material use	kg

RA	
Targeted hazard information	Unit example
Cleansing agent	-
Exposure information	Unit example
Workplace concentrations	ppm
Emission rate from chimney	$kg \cdot hr^{-1}$
Concentration in duct	%
Concentration in usage	%
Concentration in waste water	%
Working time for dealing the substance	$hr \cdot day^{-1}$
The number of worker (Cleaning, In same room, Other working)	Person
Ambient surrounding	-
Height of chimney	m above the ground
Area of outlet duct	m^2
Use condition	kPa, deg C

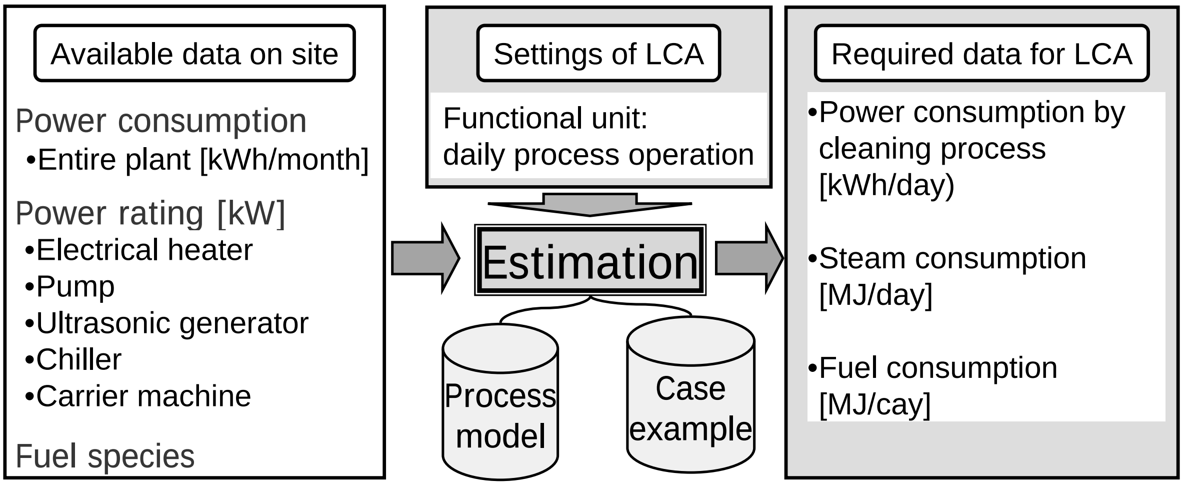


Figure 5-19 Example of estimation requirements for assessment

Table 5-2 Information required for the specification of the consumptions of electricity and fuel/steam on cleaning process in the mechanism for EvM

	Actual use amount	Estimation 1	Estimation 2	Estimation 3	Estimation 4
Electricity	Power consumption of cleaning process [kWh•month^{-1}] Working days [day•month^{-1}]	Power consumption in entire plant [kWh•month^{-1}] Empirical ratio of cleaning process to all [%] Working days [day•month^{-1}]	Power rating of each device [kW] Working time of each device [hr•day^{-1}] Working days [day•month^{-1}]	Power voltage of each device [V] Average electric current of each device [kA] Working time of each device [hr•day^{-1}] Working days [day•month^{-1}]	Estimated heat duty [MJ•hr^{-1}] Working time of heater [hr•day^{-1}] Working days [day•month^{-1}]
Steam/Fuel *Steam includes indirect heat medium	Fuel use for steam [MJ•month^{-1}] Working days [day•month^{-1}]	Steam use [MJ•month^{-1}], [kg•month^{-1}], [m3•month^{-1}] Boiler efficiency [MJ-steam•MJ-fuel^{-1}] Fuel species [-] Working time of boiler [hr•day^{-1}] Working days [day•month^{-1}]	Steam use [MJ•month^{-1}], [kg•month^{-1}], [m3•month^{-1}] Fuel species [-] Working time of boiler [hr•day^{-1}] Working days [day•month^{-1}]	Estimated heat duty [MJ•hr^{-1}] Fuel species [-] Working time of boiler [hr•day^{-1}] Working days [day•month^{-1}]	

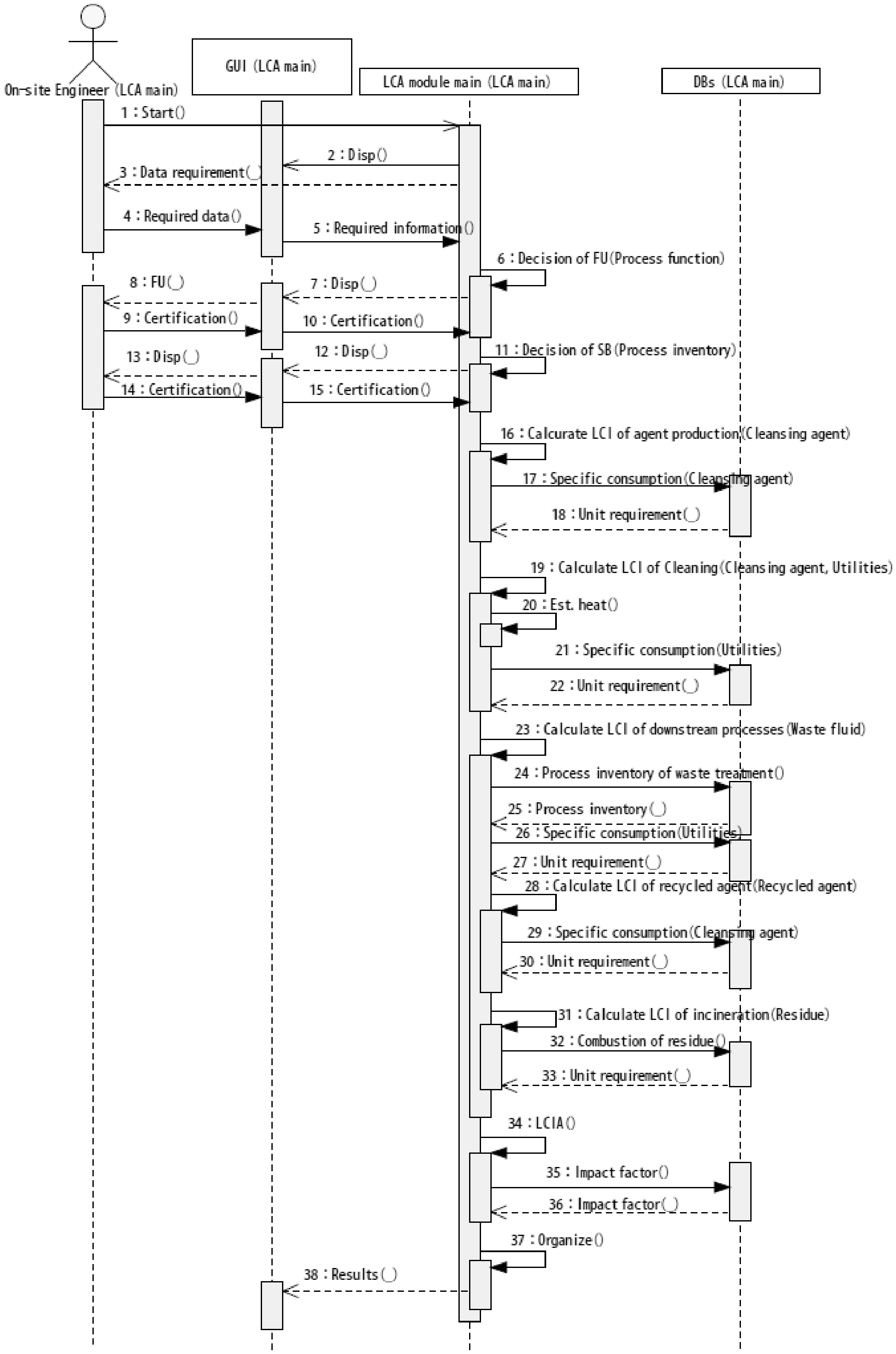


Figure 5-20 Sequence of the main LCA module on cleaning process in the mechanism for EvM (UML sequence diagram)

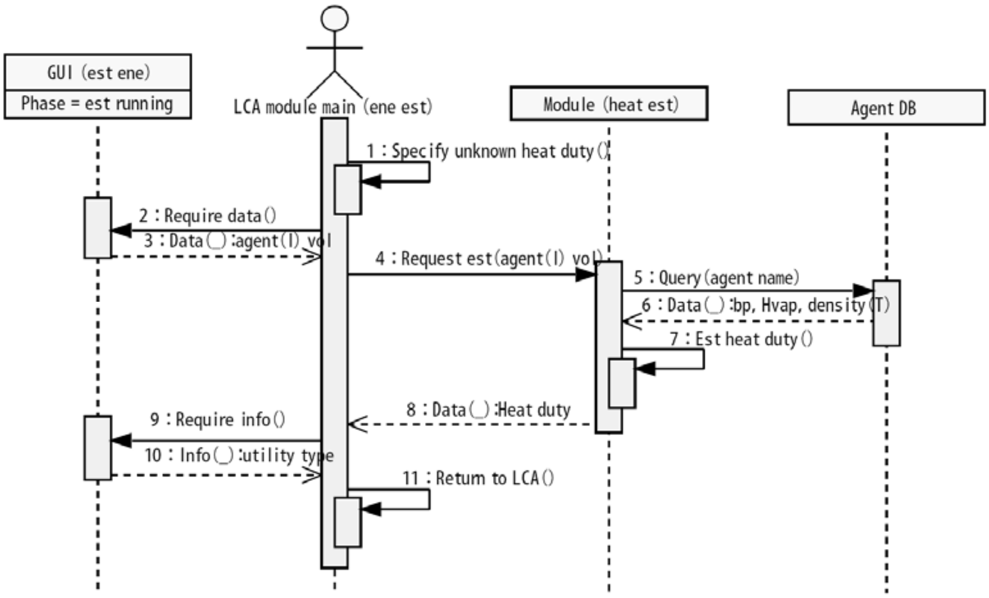


Figure 5-21 Sequence of the estimation of utility use at cleaning process in the mechanism for EvM (UML sequence diagram)

Figure 5-22 shows the sequence of the main RA module on a cleaning process in the mechanism for EvM. The main concept of this sequence is similar to that of LCA sequence that is started at the collection of required data followed by the main calculations. The main calculation of RA is the identification and evaluation of risk, which can be predefined and grouped into three types of cleansing agent. **Table 5-3** organizes required risk evaluation according to the types of cleaning processes classified by cleansing agents. The cleaning processes as solvent, aqueous, and flammable/explosive solvent are the main processes in metal cleaning processes. Each process has the dominant risks to be addressed, and the evaluation sequences can be recognized. **Figure 5-23** shows the sequence of the risk identification and evaluation on cleaning process utilizing solvents as cleansing agent. The dominant risks by nonflammable solvent should be health risks. For the evaluation, PDI and the maximum exposure concentration can be the key data dominating chronic and acute health risks, respectively. In the evaluation of neighborhood risks, diffusion models should be employed to estimate the concentration. At the end of evaluating risks, all available indicators are applied to indicate the existence and the degree of risks, and then, they are transferred to AGM/RIM

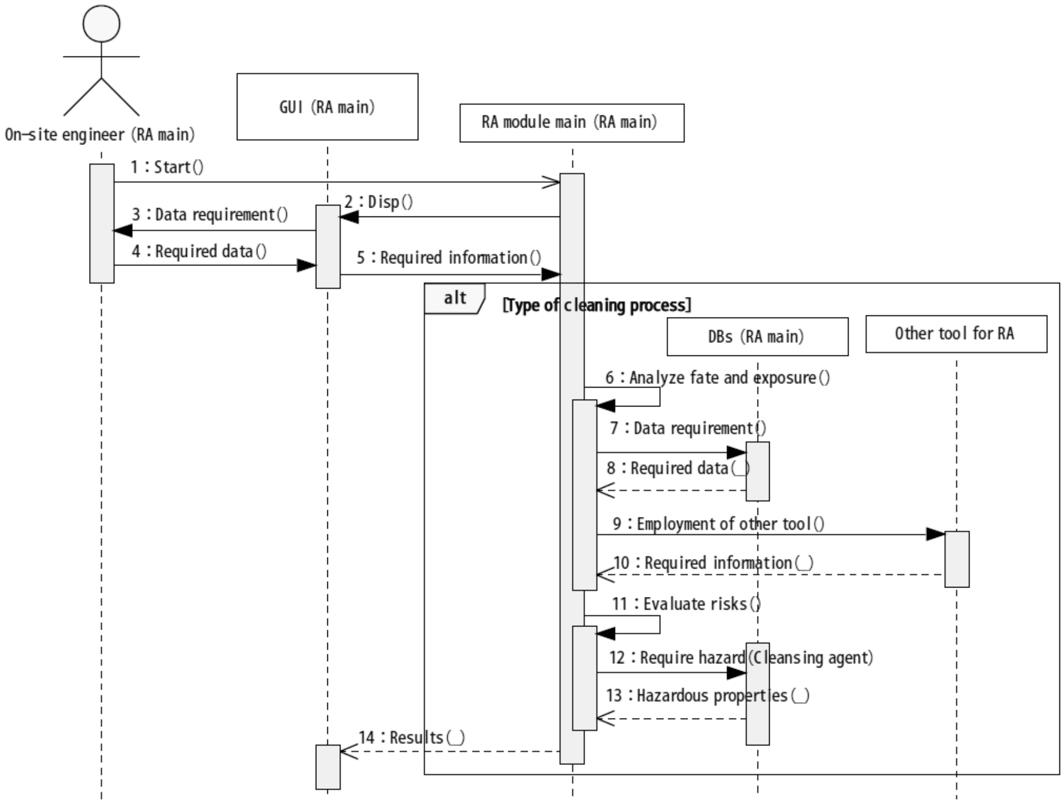


Figure 5-22 Sequence of the main RA module on cleaning process in the mechanism for EvM (UML sequence diagram)

Table 5-3 Required risk evaluation according to the types of cleaning processes classified by cleansing agents

Cleansing agent	Safety risk	Health risk	Environment risk
Solvent (chlorinated/ brominated/ fluorinated)	Occupational acute health (I)	Occupational chronic health (I), Neighborhood chronic health (I)	Soil pollution (S)
Aqueous detergents and surfactant	Occupational safety (D)	Occupational health (D)	Local aqueous ecology (Dis)
Flammable/ explosive solvent (hydrocarbon/ alcohol	Occupational safety (Phy)	Occupational chronic health (I)	Soil pollution (S)

(*) I: inhalational, D: dermal, O: Oral intake exposures, P: Physical hazard, S: Sink, Dis: Discharge

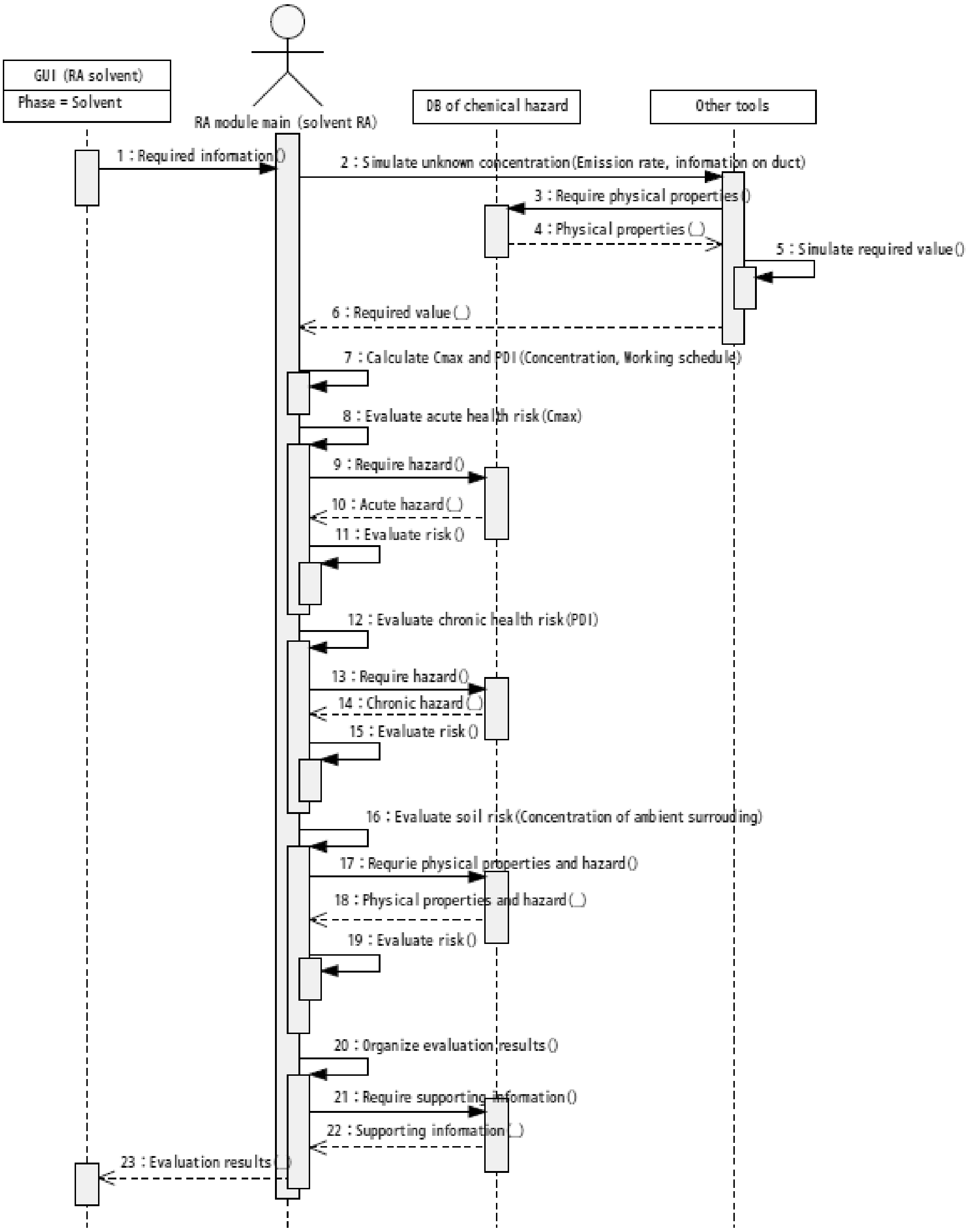
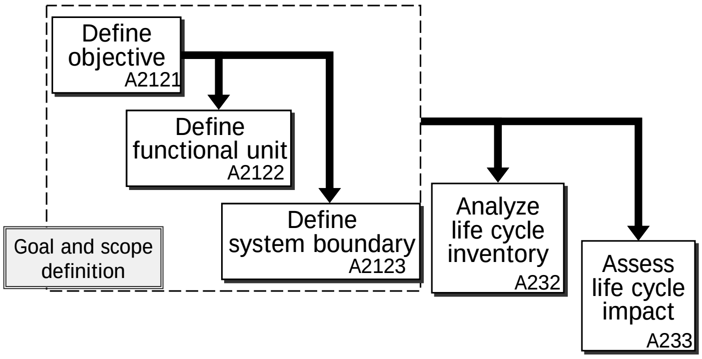
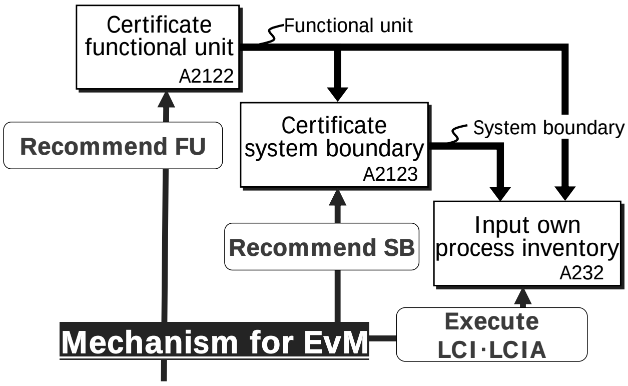


Figure 5-23 Sequence of the risk identification and evaluation on cleaning process utilizing solvents as cleansing agent in the mechanism for EvM (UML sequence diagram)



(a) Required activities for LCA



(b) Required activities for LCA with the mechanism for EvM

Figure 5-24 Activity redefinition by the mechanism for EvM

Activity Redefinition

Almost all required activities are conducted by the mechanism for EvM. All the user has to do is to certificate the assessment settings and input the inventories of their own process as an example of LCA is illustrated in **Figure 5-24**. The EvM mechanism requires various connections with other mechanisms for RSM, AGM, PSM, and RIM. The former three mechanisms generate required information for evaluations, and the last one is the receiver to present the evaluation results to system users.

5.3.2. Activation of Risk Specification

Needs of Mechanism

As shown in **Figure 5-3**, the objective settings, provided from activity A21 (activity A41), must become the strongest constraints on the execution of assessments. In the sub-activities of A21, there are compositional activities for each assessment methodology. In such activities, researchers explicitly and implicitly utilize knowledge and skill on the assessments, one of which is represented as a mechanism "understanding of assessment methodologies" in **Figure 5-5**. At the same time, they can specify risk indices and indicators intuitively and logically by making full use of their cumulated empirical knowledge on assessments, which can associate given process features with such assessment settings.

In addition, even though researchers can specify the plausible risk indices and indicators for a process feature, the risk specification may not be sufficient to achieve scientifically-validated consideration as explained in section 4.2. To implement proposed risk specification method, relational database (RDB) on assessment methodologies and process characteristics, and adequate query system for such RDB might be necessary. Such system should be able to cumulate the knowledge and case examples on process design based on evaluation results.

User Requirements Definition

The user requirements of a mechanism for RSM should be composed of the system input/output definition and the activity relation among related viewpoints. **Figure 5-25** shows the UML use case diagram for the RSM mechanism. The input information from on-site engineers should be the process information. RSM has a role to understand the process characteristics and to specify risk indices and indicators.

Figure 5-26 is the UML activity diagram of RSM mechanism. This activity diagram is based on the process flow represented in **Figure 4-3**. Because RSM is utilized in the objective settings phase in evaluation activity, which is shown in **Figure 5-5**, EvM calls RSM, and thus, the activity flow is started at EvM. Called RSM begins to collect required process information for risk specification by posing a question to on-site engineers, who are the system users, and calling AGM/PSM. At the same time, RSM call EvM back to get the information of assessed life cycle. After organizing collected information, RSM is moving on the phase of specifying risk indices and indicators by repetition processing. This phase applies highly-developed RDB connecting life cycle inventory, chemical and hazardous property, evaluation indicator, and its required technical information databases. Implementing user's acceptances on technical data availability, the risk indices and indicators can be specified through exhaustive consideration on all kinds of existing hazard and applicable indicators. Specified items are transferred to EvM, finally.

This activity flow strongly depends on the RDB called in the specification phase. This RDB partly includes existing DBs such as LCA inventory, and chemical hazard DBs. The stored data in such DBs should be upgraded by novel attributions for risk specification. They are the temporal and spatial aspects on chemical hazardous property and evaluation indicator, which were introduced in section 4.2.

System/Data Requirements Definition

The requirements on system and data in a mechanism for RSM should be the structures of RDB on evaluation indices and indicators. **Figure 5-27** shows the E-R diagram of the proposed RDB represented by IDEF1x. This model clarifies the required entities related with risks attributable to a process setting.

Figure 5-27 includes the three entities, input, database, and output. Input entity means that the inputted process information from system users. Based on this entity, database entities with required information are related each other. The output entities become available by tracing all entities from input entities.

The search results include all risk indices and indicators originally. In this time, system users have difficulties to identify and specify appropriate items. The ranking mechanism proposed in section 4.2.4 can recommend items based on physical (scientific) exactitude, practicability (feasibility), and uncertainty (variability). This ranking mechanism should be connected with the outputted information from the RDB represented in **Figure 5-27**. All recommendation categories of all search results from the RDB are calculated, and then, the results are ordered in the recommendation. This can support system users to specify appropriate items as much as possible.

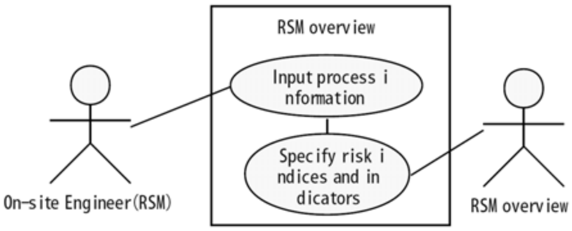


Figure 5-25 Conceptual use case of the mechanism for RSM (UML use case diagram)

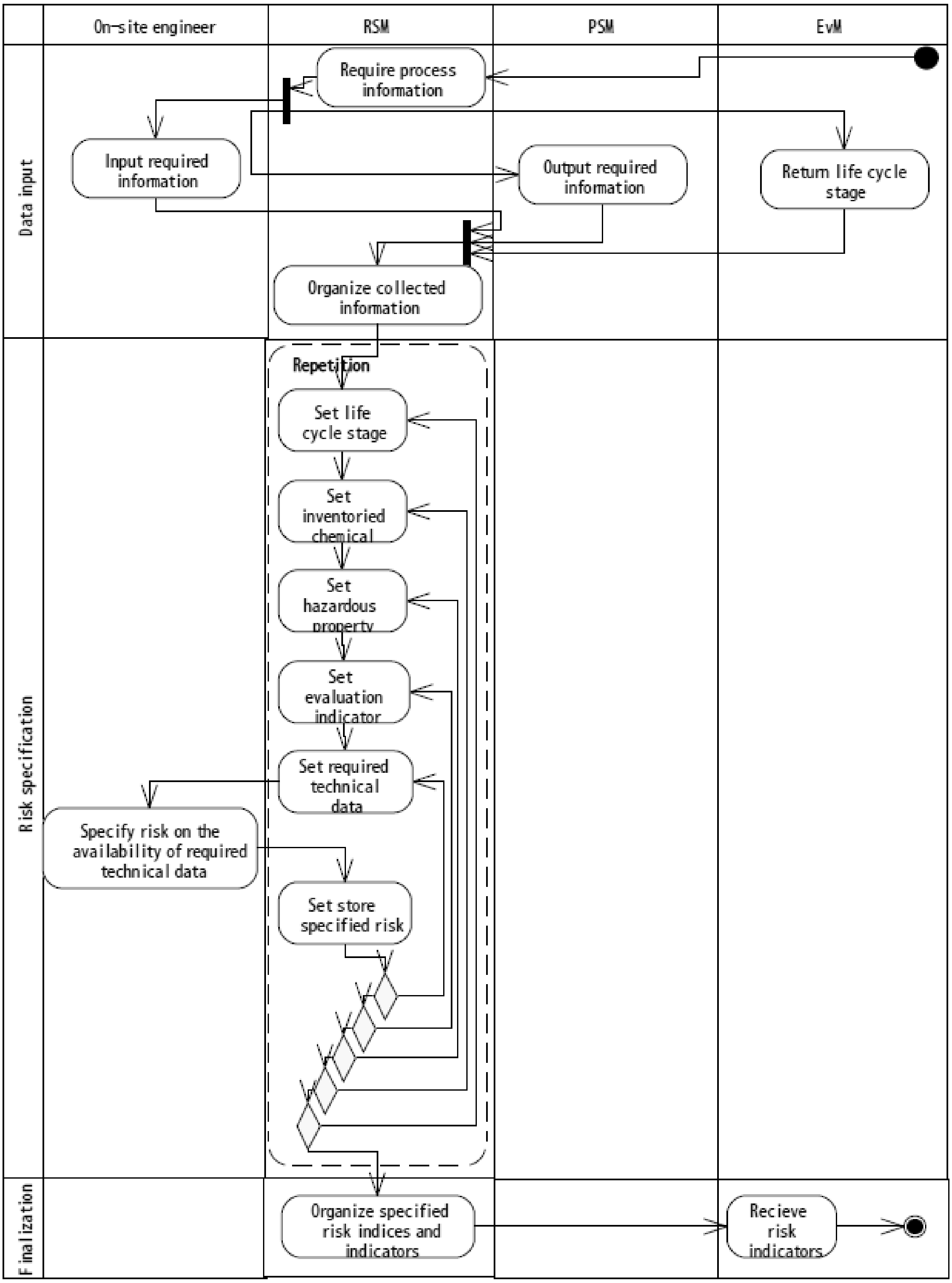


Figure 5-26 Activity flows in utilizing the mechanism for EvM (UML activity diagram)

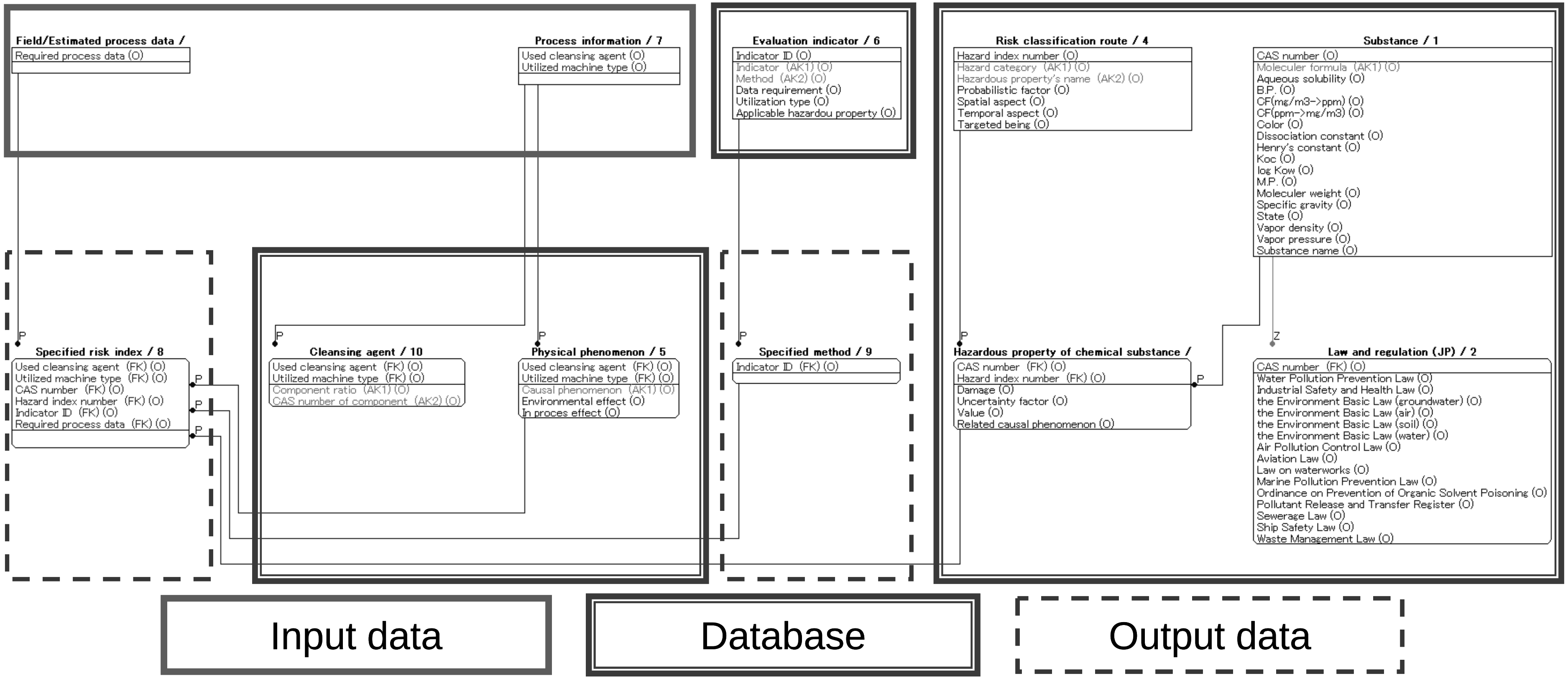


Figure 5-27 Entity-Relation diagram of the RDB and query system implemented in the mechanism for RSM (IDEF1x diagram)

Activity Redefinition

Utilizing the defined mechanism for RSM, the activity represented in **Figure 5-2** has changes in the structures and concepts. The dominant change should be the kinds of required activities. The contents of concepts between activities might be improved at the same time. This is because the proposed mechanism associates existing knowledge on risk evaluation.

5.3.3. Activation of Alternative Generation

Needs of Mechanism

Encompassing alternative generation has large potentials to seek optimal process improvement. Whereas it cannot be viable in practice for engineers, computer system has the great ability to seek alternatives corresponding with given conditions from numerous candidates. On the other hand, the given conditions specifying the practicable candidate processes sometimes include large numbers of objective functions. As well as quantitative constraints, qualitative constraints such as regulations can exist, which are difficult for computer system to address. To take advantages both of the bandwidth of computer system and heuristics by engineers, a mechanism enabling supports for engineers to search available technologies should be developed.

User Requirements Definition

Figure 5-28 shows the conceptual use case of a mechanism for AGM represented as a UML use case diagram. AGM can generate alternative candidate processes by searching RDB of available technical information. On-site engineers should certificate the suggested processes as viable alternative processes.

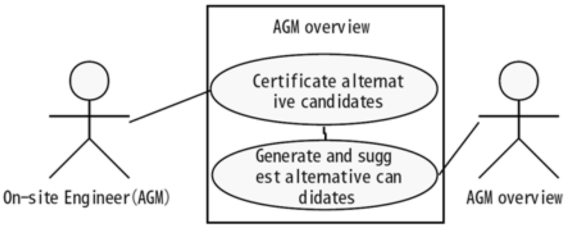


Figure 5-28 Conceptual use case of the mechanism for AGM (UML use case diagram)

System/Data Requirements Definition

The basic of the algorithm is proposed in section 4.3 as a flowchart to generate alternative candidates by decision tables. The system requirements can be proposed along with the flowchart and its function. **Figure 5-29** shows the sequence of the mechanism for AGM. In the sequence, the evaluation results are referred to identify the dominant risk factors to evaluation results. The process represented in the flowchart of **Figure 4-12** is included after contribution analysis of evaluation results as the conceptual alternative generation, which highly depends on the tables. Therefore, the developments of such decision tables are the important to associate the knowledge on process and to activate this sequence. Based on the results of the contribution analysis and conceptual alternative generation, the alternative candidates are ordered by the rank of contribution of risk factors. After this general alternative generation, detail design is fulfilled for the engineering adjustment of alternatives into the actual plant by the interactive generation with users.

The important data requirements are the knowledge on physical phenomena in processes. **Figure 5-30** shows the E-R diagram of the RDB and query system implemented in the mechanism for AGM. This information model must be maintained not only for utilizing it during alternative generation sequence, but also for the reference knowledge to establish decision tables.

Activity Redefinition

The proposed mechanism for AGM can save the activities to search and check up available technologies for alternative candidate processes. Because this AGM includes the E-R with evaluation indicators, the alternatives can change the LCA and RA results. Note that it cannot be revealed whether the alternative can improve the evaluation results. It should be verified by the evaluation of alternative candidate processes with a mechanism for PSM. The suggestion by AGM means that the suggested alternatives have strong relation with evaluation results and they seem to be able to improve the physical phenomena linking evaluation indicators.

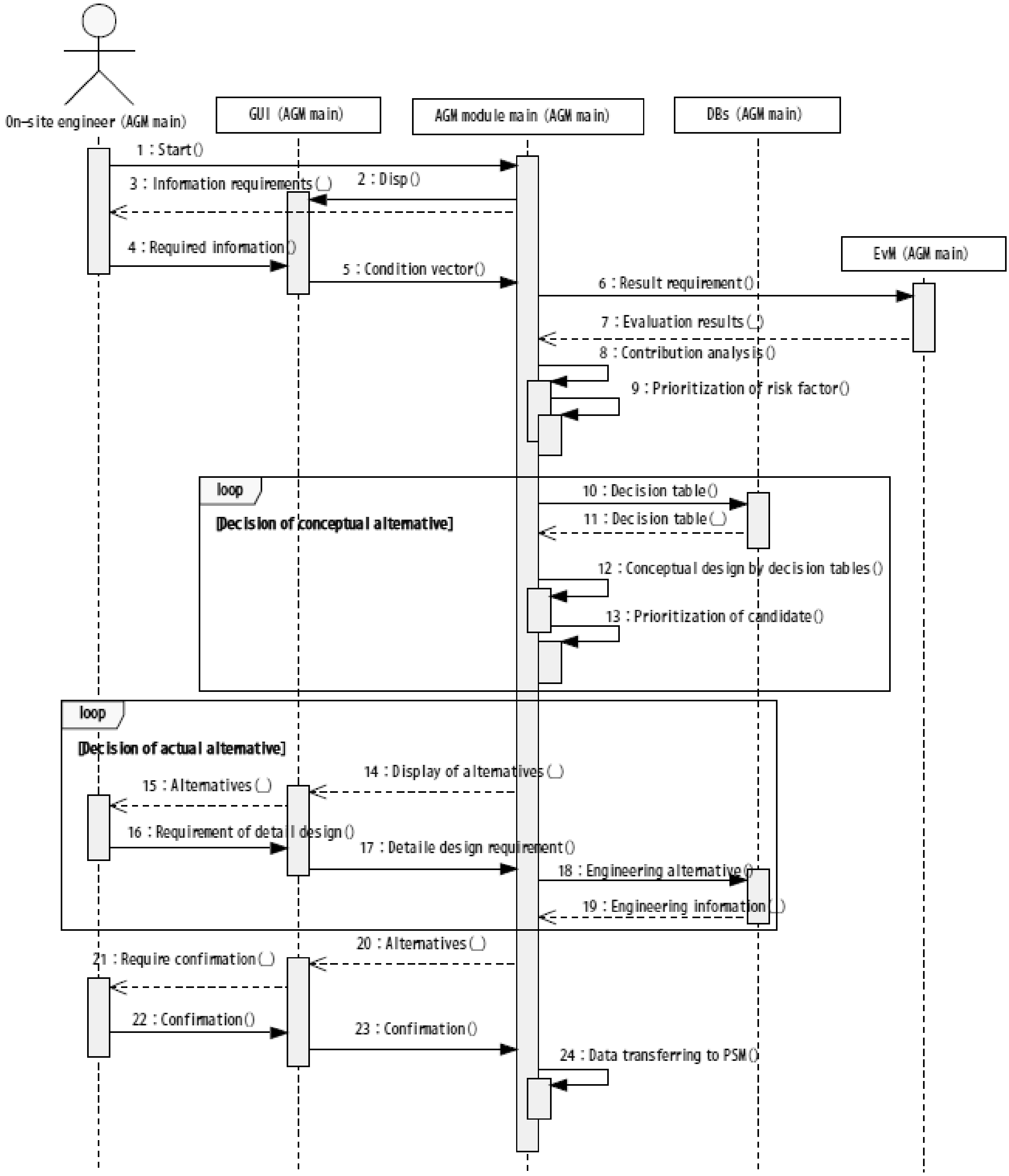


Figure 5-29 Sequence of the mechanism for AGM (UML sequence diagram)

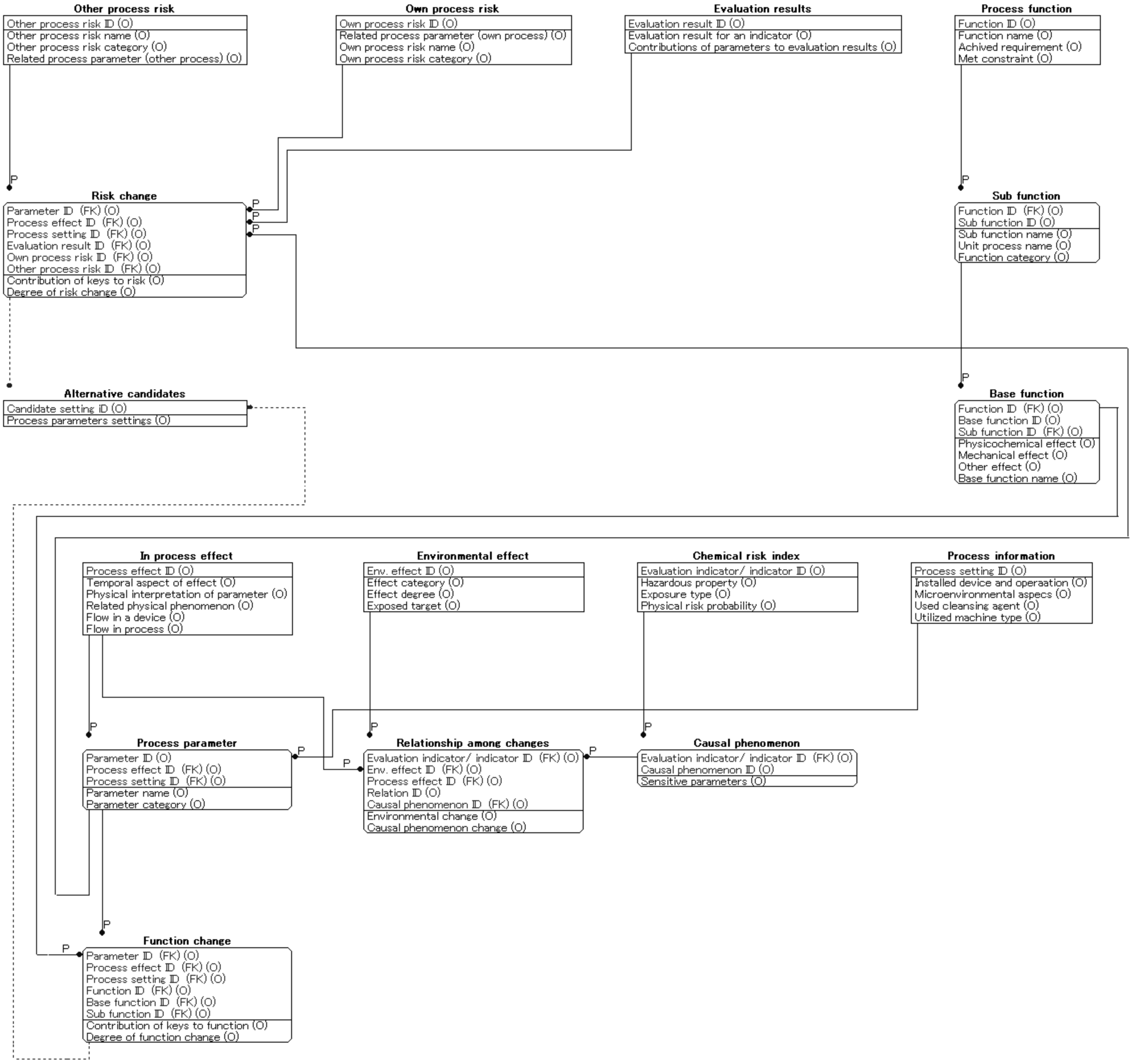


Figure 5-30 Entity-Relation diagram of the RDB and query system implemented in the mechanism for AGM (IDEF1x diagram)

5.3.4. Activation of Process Simulation

Needs of Mechanism

Alternative candidate processes under individual conditions does not exist actually, and thus, the process data required for LCA and RA should be estimated by process models. As introduced in sections 4.4 and 4.5, process models can be developed through reasoning and associating evidences on physicochemical and statistical approaches. There are various process models representing different aspects of process. The estimation of process data should be able to reflect the total effects caused by the alternation of process parameters. Therefore, the integration and differentiation of obtained models should become possible.

User Requirements Definition

A mechanism for PSM is a tool enabling the association of obtained process models and the estimation of process data. **Figure 5-31** shows the conceptual use case of such mechanism. By inputting process information, PSM can simulate and estimate the process data required for LCA and RA, which can be instructed by EvM. The process information must include all process parameters related with the physical phenomena of causing risks and achieving process functions.

Activity Redefinition

PSM is usually utilized at the situation when alternative candidate processes are assessed. At that time, all activities to be performed by on-site engineers is to confirm the data settings. In addition to such situation, this model may be utilized as the trial to seek the alternative at alternative generation. This time needs the input of process information.

5.3.5. Activation of Risk Interpretation

Needs of Mechanism

Various risk indices and indicators are available in LCA and RA. Some indicators have a criterion of judging the acceptance of risk such as threshold of exposure and uncertainty value for MOE. Others have no criterion to judge it, i.e., less is better. Exact interpretation should be practicable by decision makers.

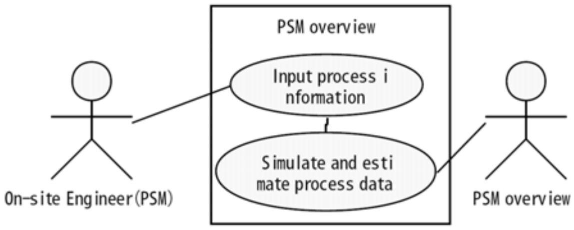


Figure 5-31 Conceptual use case of the mechanism for PSM (UML use case diagram)

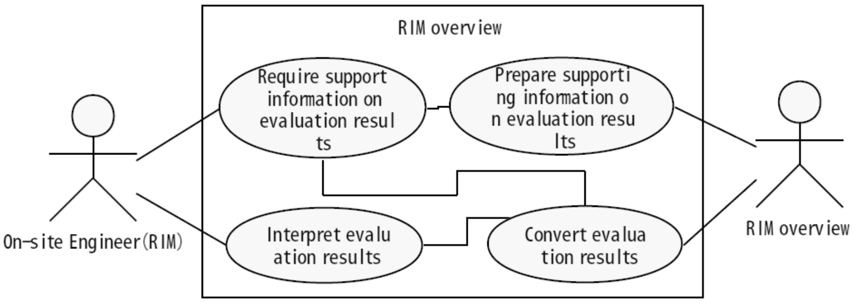


Figure 5-32 Conceptual use case of a mechanism for RIM (UML use case diagram)

In risk interpretation, graphical illustration has a large potential of dominating the results of interpretation. In addition, optional methods of interpretation can be available such as contribution analysis for alternative generation, sensitivity and uncertainty analysis for decision, and normalizing, grouping, and weighting for aggregation. To utilize such technical methods appropriately, a supporting mechanism should be able to connect the evaluation results from EvM with the representation by the GUI.

User Requirements Definition

Figure 5-32 shows the conceptual use case of a mechanism for RIM. This use case diagram shows the interpretation for decision making. The system user and RIM should be interactively convert the evaluation results. At the end of the activation of RIM, an alternative candidate process is decided or the further improvement is required for AGM. In this regard, alternative scenarios and processes can be specified based on the results of interpretation, which should be transferred from RIM to AGM.

RIM for alternative generation is just the interface of converting evaluation results into the contribution analysis results. The categories of contribution are set as default for cleaning process, which are agent production, agent emission, fuel production, fuel combustion, and waste output.

Activity Redefinition

As explained above, the required activity of system users is decision making with interactive conversion of evaluation results. On this meaning, the activities are not varied dramatically. The conversion of evaluation results can become more useful with the mechanism, because the major optional methods and visualization can be practicable by it. Additional information becoming support for the interpretation of evaluation results can also available such as the statistical data on local risks and global impacts obtained by the researches of national institutes.

5.4. Conclusion

Risk specification, evaluation, risk-based alternative generation, process simulation, and interpretation can be essential steps for appropriate decision making considering risk. The knowledge and method activating them were connected and defined as the structure of mechanism for risk-based decision making, which was derived from the structuration of knowledge on process design and evaluation. The interaction of each method were analyzed and implemented into a business model visualized by IDEF0 function modeling language. In this model, the integrated procedure of process evaluation and information flows among five mechanisms can be clearly defined. At the same time, the information and system models required for the enhancement of risk-based decision making can be discussed and modeled by IDEF1x and UML information modeling languages. IDEF1x can link to the development of databases cumulating knowledge on process design and evaluation. UML can define the requirements of software information system activating risk-based decision making. The combination of these modeling languages can visualize the achievements of knowledge structuration.

Chapter 6. Applicability of Knowledge Structuration

6.1. Introduction

Based on the knowledge structuration introduced in Chapter 2, the problem on risk-based decision making in actual case study was addressed in Chapter 3, and then, the knowledge for the enhancement of practicability was structured in Chapter 4. The knowledge was related with the process design and evaluation, and converted into practical style through the integration with business activity model and practicable one through the activation by software information system in Chapter 5.

In early design phase of software systems, the role of researchers becomes important to stimulate and activate robust and flexible system. Researchers can specify the activities and information required for risk-based decision, appropriately and systematically. Although generalization of method has been carried out by researchers, systematization here needs the representation of method by common modeling language to let them understandable for system developers. Moreover, researchers have the capacity of customizing method along the individual conditions of decision makers, which is achieved through a cooperation with system users.

This chapter presents the activities required for a problem-oriented knowledge structuration approach to general problem with case examples. In the procedure of knowledge structuration, the proposed business activity and software-information system models can be applied as a template of them toward general problems. The generalized templates derived from models proposed in Chapter 5 are introduced. Additionally, the established structured knowledge on process design and evaluation is also discussed as the general solutions for other problems on risk control or environmental management. The generic applicability of knowledge structuration and structured knowledge through the previous chapters is certificated by the comparison with existing knowledge management approach in process design, PDCA cycle approach.

6.2. Problem-Oriented Knowledge Structuration Approach

Figure 6-1 illustrates the procedure of knowledge structuration for implementing risk-based decision making into practice. The procedure is composed of R&D for risk-based decision making, BPR of actual decision process, requirements definition enabling an effective and accurate communication with system developers, and system development. Along with this procedure, a researcher can play a role of defining system requirements by developing activity and system models. Additionally, the procedure is based on the knowledge structuration as shown in **Figure 6-2**. Each step is explained below with required IDEF and UML diagrams.

R&D for Risk-Based Decision Making

This phase starts with the identification of actual problems on risk-based decision making. This identification has to specify the premises and situation demands for validating effective existing solution to be implemented into practice. At this phase, the actual individual conditions should be taken into account as evidences of problems, and then they are reasoned and converted into formalized understandings on the actual conditions of problem. Based on the carefully formalized knowledge on problem, available technologies are reviewed whether they are applicable for identified problem. Then, existing knowledge and related empirical actions are associated as solutions for the problem. In this regard, knowledge should be classified and divided into several parts to simplify the association and to enhance the re-usability of knowledge. In this time, association means the systematization of individual classified knowledge and can be extended to combine with all of them to a knowledge network. If no existing knowledge and empirical actions can resolve the problem, a novel technology should be developed on the basis of analysis results in problem identification and judgment concluding no existence of applicable technology.

So far, this R&D phase can be regarded as the research activities already performed by researchers on risk control and environmental management. In this regard, however, for practicable knowledge structuration, the understandings of researchers to the qualified solution to problem must be available for system developers. Activity modeling is the useful to let them understand the solution as business model. IDEF0 activity model can behave the communication tools for BPR implementing developed solutions.

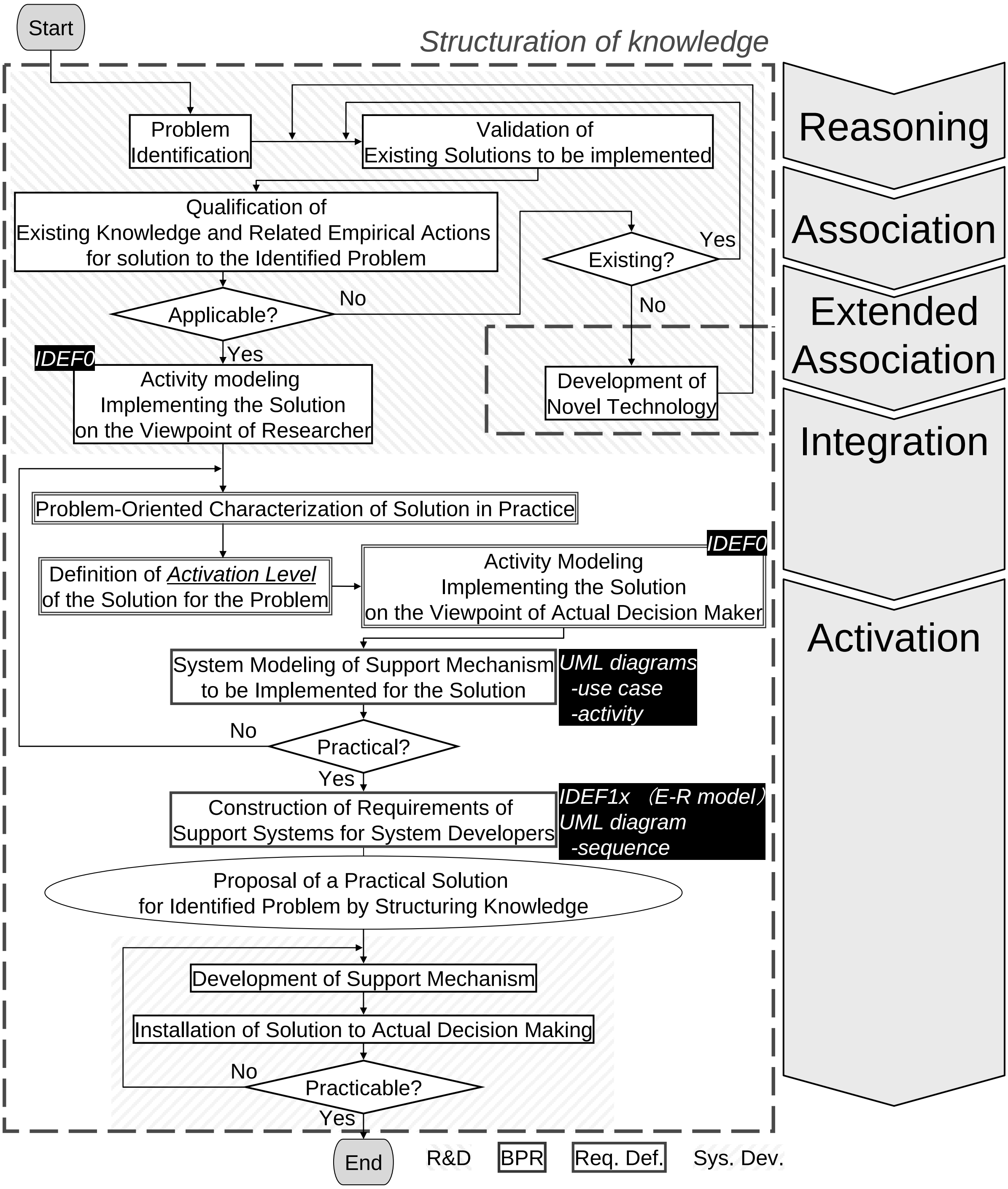


Figure 6-1 Procedure of problem-oriented knowledge structuration by cooperation with researchers and system developers

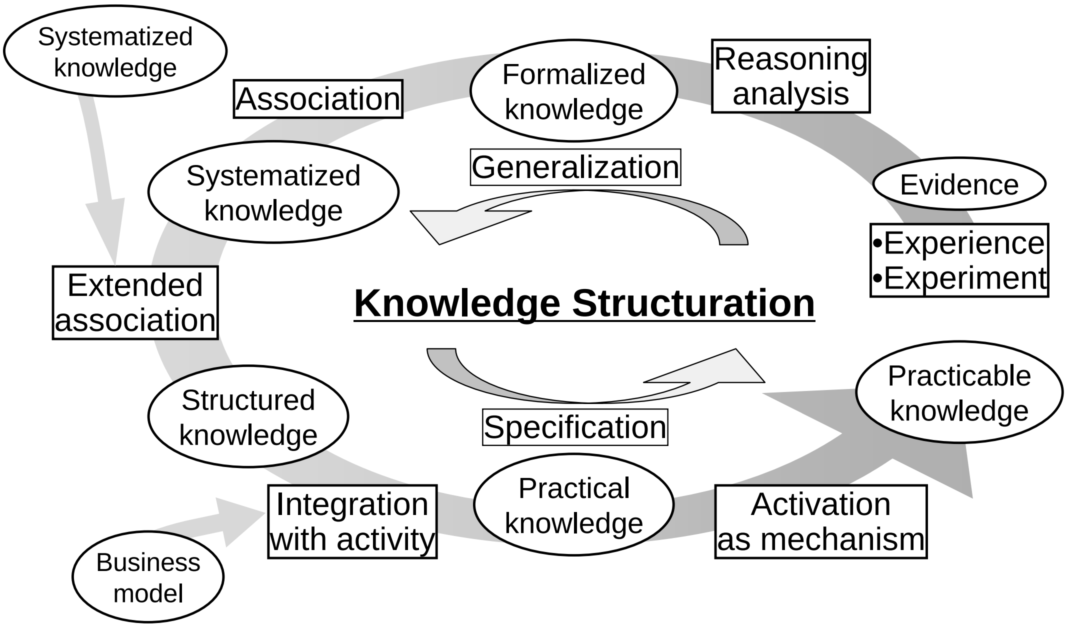


Figure 6-2 Knowledge structuration circulating knowledge conversion (reprint of **Figure 2-1**)

BPR of Actual Decision Process

This phase promotes the method scientifically proposed in R&D phase as a practical method in actual business model. This means that this phase execute BPR of present decision process to implement the proposed method. This BPR phase composes a part of the integration of knowledge with business activity model to convert knowledge into practical one. A strong and interactive collaboration with system users is a vital element toward adequate BPR. By collaborating with actual decision makers, the viewpoint is analyzed; for example, solution practitioners, users of information originating from proposed solution, and persons behaving data acquisition. This analysis should finally recognize the practicable activities and available resources for the viewpoint.

All procedures in BPR should be based on the individual conditions of actual decision makers, or system users. A commonly existing activity, for example LCI, should be differently supported on such conditions. This can be represented in IDEF0 model developed in this phase. This model is based on the premises of actual decision makers, which means that the IDEF0 model developed in R&D phase should be re-considered to identify, decompose, and redefine the impracticable activities for them. Main difference between these IDEF0 models is the simplification degree of activities in data acquisition and execution of scientific method. In this regard, however, such simplification degree should be different on individual conditions of decision-maker. This research defined an indicator of such degree, activation level shown in **Figure 6-1**. If the activation level is higher, the activities in business model should be defined as easier ones with stronger supportive software system. Based on this level, the requirements of software system are defined.

Requirements Definition Enabling an Effective and Accurate Communication with System Developers

Based on the activity model developed and activation level defined in BPR phase, this phase performs the requirements definition for software systems development. The first step is drawing use case and activity UML diagrams. These diagrams visualize the actual use case of software systems and information relay among multi viewpoints, i.e. swim lane. Because the way of drawing these diagrams does not need specialized knowledge on software system, researchers can execute this step without cooperation from system developers. If the activities demonstrated in developed use case and swim lane are practical, the development proceeds to system/data requirement definition from user requirement definition, which is the phase of activation of knowledge.

Detail modeling of information for software systems development might need the fundamental knowledge on information technology. From this phase, cooperation with system developers should be attained hopefully. In this regard, however, foundation of information modeling can be addressed with a bit of knowledge on computer algorithms and logics. IDEF1x model, which can be called as E-R diagram, is one of the basic information modeling language. This can employ the visualization of logical relationship between entities. Additionally, a sequence UML diagram can be developed by researchers as a prototype. The adequate sequence of activities of decision makers with software systems is one of the most important user requirements. If researchers can be involved in the development of sequence UML diagram, it may lead to enhance the quality of completed system.

System Development

Developed IDEF and UML diagrams can be regarded as the proposal of a practical solution for identified problem by structuring knowledge. User and system/data requirements are enough to submit as a proposal to system developers. In this time, researchers can perform development of foundation of system by developing prototype system on available software, such as Microsoft$^{\mathrm{TM}}$ Excel ® or MathWorks$^{\mathrm{TM}}$ MATLAB ®. These models and prototype software can behave a considerably detail and concrete requirements for system developers.

6.3. Templates of Risk-Based Decision Making on Process Design

The procedure of knowledge structuration shown in **Figure 6-1** and the results of it might depend on the practitioners under individual conditions including approach, target, previous knowledge, and skill. This section presents the templates of the procedure of knowledge structuration, derived from the previous chapters. The templates are prepared for effective and appropriate structuration of knowledge, especially in problem identification, knowledge on process design and evaluation, and business activity and information system models.

Table 6-1 organizes the knowledge conversion during structuration on process design and evaluation. This is the overview of knowledge structuration on process design and evaluation, which can be adopted for any case of designing a process utilizing chemical substances. This section shows the templates of stimulating and enabling such knowledge conversion.

6.3.1. Strategic Problem Identification

Table 6-2 organizes the template of strategic problem identification on the basis of the process design in metal cleaning process and chemical plant. The first and second columns are the template of problem identification. It indicates the perspectives in identifying problem on risk-based decision making. They are mainly divided into two aspects: knowledge on process design and evaluation, and business activity and software information system model. The perspectives on knowledge to be implemented into practice have five categories, which are related with RSM, EvM, AGM, PSM, and RIM. These five categories can be the essential for structuring knowledge toward appropriate process design. The problem identification on the modeling of business activity and information system should focus on decision-maker, objective, existing business model, and activation need. The first three categories are necessary for business modeling, and the information system should be modeled on activation need with developed business model.

Table 6-1 Knowledge conversion during structuration on process design and evaluation

Evidence	Formalized knowledge	Systematized knowledge	Structured knowledge	Practical knowledge	Practicable knowledge
·Accidents and failures ·Toxicity experimental results ·Results of measurements ·Sense of value	·Existing hazard ·Risk factors in process ·Historical case examples ·Accidents and failures knowledge	Risk specification method -Laws and regulations -Empirical criterion -Chemical hazard	Pentagonal structure of knowledge network among methods for risk-based decision making	Effectively distributed knowledge in actual business activities keeping connecting each other	Immediately applicable tools for actual decision makers
·Emission of chemical substances into the environment ·Exposure to chemical substances ·Occurrences of risk and impact	Indicators representing risk and impact qualitatively and quantitatively	Evaluation method -LCA -RA -Feasibility assessment			
·Process data ·Experimental results ·Heuristics on process phenomena	·Physical understandings of process phenomena ·Risk-process-function linkage model ·Alternative decision table	Alternative generation method -Physical process model -Statistical model			
	·Physical equation of physical phenomena ·Statistical correlation between process parameters and physical phenomena	Process simulation method -Mathematical process model -Physical model -Statistical model			
·Trade-off relationship ·Uncertainty of risk ·Sense of value	·Threshold of risk ·Weighting on evaluation items	Risk interpretation method Grouping, normalization, and weighting			

Table 6-2 includes the identified information on each perspective of the problem in metal cleaning process design, which is introduced in Chapter 3. The analysis on existing problem in metal cleaning can reveal the requirements of assessing local risk and global impact, simultaneously. In this regard, however, any scientific approach for analyzing such non-monetary issues on metal cleaning processes has not been performed systematically. Law and regulation have been the only criteria for such issues. One of the reasons for it might be the largest fraction of SMEs in the industries managing metal cleaning processes, who are under the problem of lacking knowledge, skill, and fund enough to implement scientific methods into practice. The open-system processes might make it difficult to progress the scientific analysis on metal cleaning processes. The main processes before/after metal cleaning processes are ones for small lots, but multiproduct, which means that there is a significant process diversity in industry. No standard process model can be developed, and process model enabling dedication considering individual conditions has been strongly needed. With regard to business activity and information system for metal cleaning process, the unified and practicable solution have not been proposed, while there is an activity model aiming the clarification of the acquisition of engineering knowledge on metal cleaning (Fuchino 2004).

The strategic perspectives on problem identification enables the effective consideration of knowledge to be implemented and models to be developed as business activity and information system. In the previous chapters, first, the evaluation methods were developed by associating existing scientific methodologies. This is based on the identified problem showing the no existence of method of evaluating non-monetary issues in metal cleaning process. In order that the evaluation in risk-based process design can be performed appropriately, required knowledge categorized in five modules were developed. Business activity and information system models were developed for the actual implementation of such knowledge into practice. Especially in the activation of knowledge, the defined software system can support on-site engineers completely considering that decision-makers are in SMEs.

Table 6-2 Strategic problem identification on process design in metal cleaning process and chemical plant

		Metal cleaning process	Chemical plant
Knowledge on process design and evaluation	Risk Specification	·Risk due to the use/emission of cleansing agent ·Persistent avoidance of halogenated chemical ·Mild usage condition in open-system	·Risk due to the use/emission of chemical substances ·Existence of numerous number of chemicals in a plant ·Significant concern on safety risk ·Severe usage condition in closed-system
	Evaluation	·Application of PRTR registration ·Measurement and standard value on OPOSP ·Management on economic aspects ·No quantitative empirical action to non-monetary issues	·Evaluation methodologies developed in previous works ·Partly implementation by on-site process engineers ·Requirement of integrated approach for evaluation
	Alternative Generation	·Heuristics on process improvement regarding quality ·Distributed knowledge among related industries ·Uncertainties on open-system process	·Numerous applicable alternatives ·Highly-established physicochemical understandings on process functions
	Process Simulation	·No dedicated process model ·Uncertainties on open-system process	·Highly-established chemical process simulators ·Closed-system process
	Risk Interpretation	·Hazard management ·Trade-off relationship among local risk, global impact, and feasibility ·Excessive weight on results of PRTR investigation ·Constraints from other processes in supply-chain	·Mass-hazard management ·Trade-off relationship among local risk, global impact, and feasibility
Business activity and software information system model	Decision-maker	·On-site engineers at SMEs in value-added industry ·Lack of knowledge and skill of scientific methods	·Process engineering group at chemical plant
	Objective	·Risk reduction with quality maintenance ·Requirement of cost even or reduction	·Risk reduction with quality maintenance ·Requirement of cost even or reduction
	Existing business activity model	·No business activity model implementing scientific method	·Empirical process design activities introduced in literatures ·Proposed activity model implementing EHS assessment
	Activation Needs	·Requirement of software system enabling the execution of process design with the smallest activities by decision-makers	·Requirement of software system linking existing business procedure to scientific methods
Research need of identified problem		·Development of applicable knowledge ·Business activity modeling ·Software system activating knowledge highly user-friendly	·Extended association of existing knowledge on process design and evaluation ·Reviews and improvement of evaluation methods of non-monetary issues ·Business model implementing structured knowledge with adequate software tool

As well as the problems in metal cleaning, those in chemical plant process design are also analyzed and organized in **Table 6-2** to confirm the generic applicability of the templates. In this field, various approaches for risk-based process design have been performed. The overview of systematic method of designing chemical process was introduced as knowledge on the procedure of process design (Bieglar 1997; Duncan 1998), and the environmentally-conscious design strategy was organized (Cano-Ruiz 1998). Based on the proposed visions, research works on systematic and environmentally-conscious design have been conducted on the knowledge of evaluation method (Koller 2000), and alternative generation method including the consideration of evaluation approach (Chen 2004; Sikdar 2001). At the same time, some researches focused on the multi-objective decision making approach which can be the existing works on the knowledge of risk interpretation (Hoffmann 2001 Kheawhom 2004), and the systematic procedure connecting to business activity model (Sugiyama 2008b). Activity models were also developed for process design (Gabber 2004; Sugiyama 2008a). Some researches on the supports by process modeling and software information system have been proposed (Kellner 1999; Shneider 2002), and the requirement of business activity and information system modeling for implementing novel technology into practice was defined (Naka 2006).

Although the existing knowledge might be useful solution for the risk-based decision making on chemical plant process design, the research needs exist on the enhancement of the integrated applicability of such knowledge. Because the existing methods have been developed individually, the association of them into structured knowledge must be necessary.

6.3.2. Structured Knowledge on Process Design and Evaluation

Based on the identified aspects of problem on the five categories and the overview of problems shown in the last row of **Table 6-2**, knowledge is structured for appropriate risk-based decision making. **Table 6-3** organizes the research needs based on the strategic problem identification on process design in metal cleaning process and chemical plant. The template of structuring knowledge has the same components as ones of strategic problem identification. For five categorized knowledge, research needs can be specified. The structuring styles, however, are different between the knowledge for metal cleaning and chemical plant, because the situation demands of them are different. For the metal cleaning processes, because of no existing process models and trial of utilizing scientific methods of evaluation such as LCA, five categorized knowledge should be developed individually. On the other hand, for chemical plant, various types of previous researches can be available, and the association of such knowledge is one of the important tasks for knowledge structuration.

The evaluation boundaries might be other case of difference of structuring knowledge. When LCA is performed for process design, metal cleaning process design needs the evaluation on the boundary of the life cycle of cleansing agent and other process chemicals. The life cycle of raw material may not have to be included in the boundary, because the raw materials are usually decided on the constraints from other processes in supply-chain. The raw material selection is not included in the decidable range of the decision makers in metal cleaning process. In the design of chemical plant, the situation is different, because the raw material is one of the decision parameters of them. In this regard, however, although the life cycle of process chemical is included, "cradle to gate" life cycle is enough for the LCA of raw material. This is because they cannot change the downstream processes of chemical products from chemical plant.

Process modeling for alternative generation and process simulation has also difference. The considerable features of metal cleaning processes might be that they are open-system processes and that they have significant process diversity. The first feature needs the application of CFD analysis and the association of empirical knowledge for reducing uncertainties. The second one must be taken into account to decide the process parameters to be given at the alternative generation and simulation.

The templates of structured knowledge is illustrated in **Figure 6-3**. Although the consideration of situation demand in each identified problem for structuring knowledge in detail, the overview of knowledge on process design and evaluation can be organized as the pentagonal structure composed by five categorized knowledge: RSM, EvM, AGM, PSM, and RIM. These knowledge categorization can be applicable for process design, especially for process improvement, or retrofitting design.

Table 6-3 Research need based on the strategic problem identification on process design in metal cleaning process and chemical plant

		Metal cleaning process	Chemical plant
Knowledge on process design and evaluation	Risk Specification	·Basis of the hazardous properties of cleansing agent ·Possible risk indices from the usage conditions ·Life cycle of process chemical ·Limited life cycle of raw material	·Basis of the hazardous properties of chemical ·Possible risk indices from the usage conditions ·Life cycle of process chemical and raw material
	Evaluation	·Life cycle assessment ·Risk assessment ·Assessment on the feasibility of alternatives	·Life cycle assessment ·Risk assessment ·Assessment on the feasibility of alternatives
	Alternative Generation	·Process modeling of open-system process necessitating the application of CFD ·Association of empirical and physicochemical analyses on process ·Process modeling on assessment ·Systematization of engineering knowledge	·Existing process models ·Association of empirical knowledge ·Process modeling on assessment ·Systematization of engineering knowledge
	Process Simulation	·Process modeling of open-system process necessitating the application of CFD ·Association of empirical and physicochemical analyses on process ·Process modeling on assessment	·Existing process models ·Association of empirical knowledge ·Process modeling on assessment
	Risk Interpretation	·Multi-objective risk-based decision making	·Multi-objective risk-based decision making

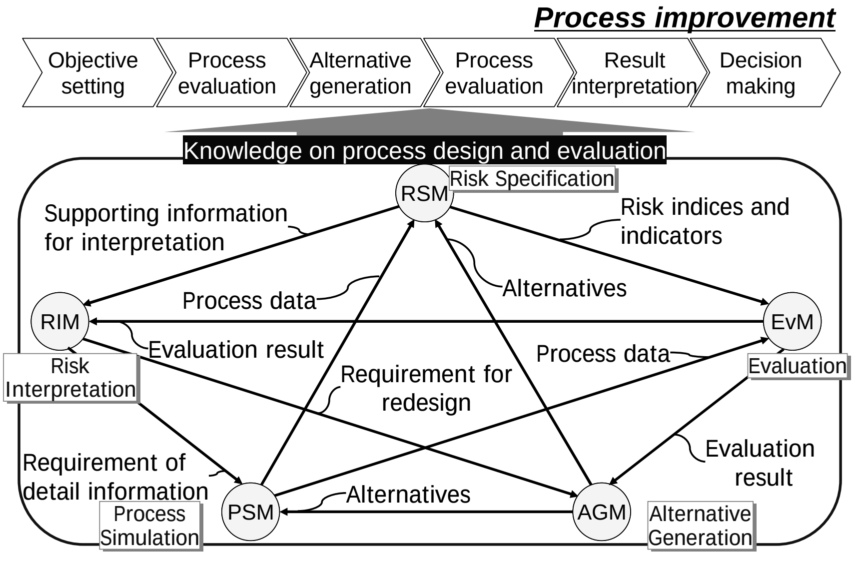


Figure 6-3 Process improvement and knowledge on design and evaluation

Knowledge on Process Design and Evaluation in PDCA cycle

As the solution for the problem on risk-based decision making in metal cleaning process, a method of evaluation and the required knowledge were proposed and developed in Chapter 3 and Chapter 4, respectively. The knowledge on process design and evaluation is divided into five categories; risk specification, evaluation, alternative generation, process simulation, and risk interpretation. The cycle including plan, do, check, and act (PDCA) has the major generality in various process improvement. The five categorization in this research can be interpreted with the four steps of PDCA.

PDCA cycle is an iterative four-step problem-solving process typically used in business process improvement. Plan phase establishes the objectives and processes necessary to deliver results in accordance with the expected output. Do phase implements or simulates the new processes. Check measures, assesses the new processes, and compares the results with the expected results based on the established objectives. Act phase analyzes the cause of different identified in check phase and then generates the countermeasures to eliminate the difference. After the act phase, the procedure goes to the plan phase again, and spiral up as continuous improvement. **Figure 6-4** shows the structured knowledge on the procedure of PDCA cycle. It is schematically verified that the systematized and structured five categorized knowledge can include the PDCA cycle, and at the same time, enhance the functions of each activity in PDCA phases.

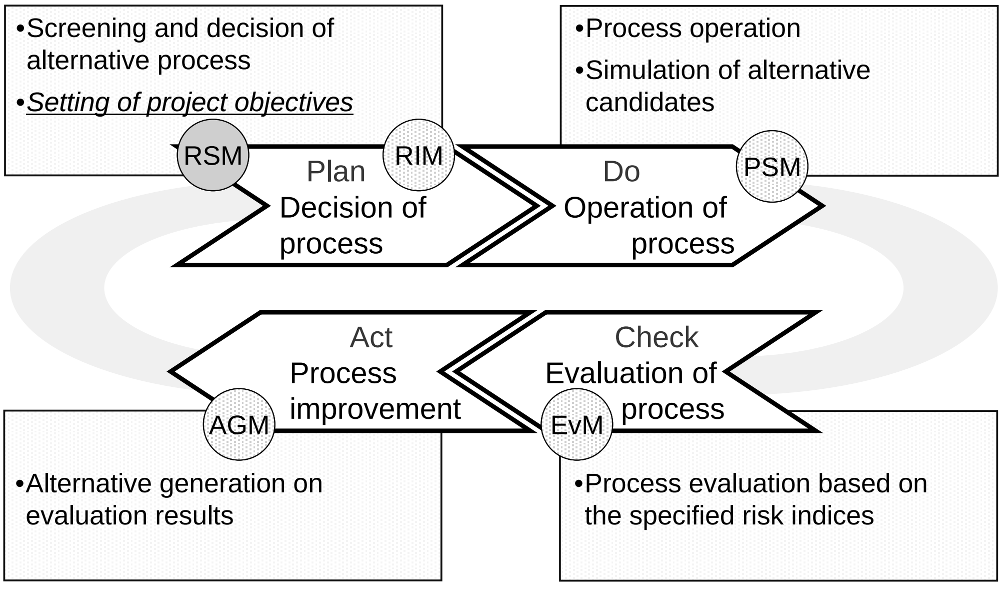


Figure 6-4 Structured knowledge on the procedure of PDCA cycle

Plan phase starts the process development based on the interpretation of process functions, relationship with constrains, conditions around the product, and chemical risk. Risk interpretation method (RIM) is the method systematizing required knowledge for interpreting such conditions. At this time, the indices to be considered cannot be specified easily. At the ordinary process design, the objective functions have been economic profits or product qualities under the constraints of non-monetary issues such as regulations. In the risk-based decision making, risk indices must be included in the objective functions of process design. The specification of indices require the well-understandings of risk potentially caused by decisions. In this phase, the appropriate objectives of project, or PDCA, must be defined. Risk specification method (RSM) is the method for such requirement. RSM is not included in PDCA cycle explicitly. The RSM can take into account the needs from the social sense of values, as well as the scientifically-logical risk indices.

Planned activities are implemented into practice in Do phase in PDCA. It includes the actual execution and simulation by process models. Process simulation method (PSM) can be the systematized tools for simulation without actual executions. Pilot and mini plant constructions are ones of the ways of testing the planned activities.

Executed activities must be checked by assessment methodologies. The indices of assessment are defined in plan phase, which are based on RSM. Collaborating with evaluation method (EvM) and RSM, the check phase can be appropriately done.

Act phase should decide the countermeasure to the results of check phase. Alternative generation method (AGM) can address the decision of the following actions based on evaluation results.

Because the PDCA cycle has four steps of activities, it seems that four categorized knowledge might be necessary. This research, however, reveals the necessity of five knowledge for risk-based decision making. The special knowledge might be RSM, which can take into account the diversifying needs of assessment in process design by systematizing the knowledge on risk control. This discussion with the relationship with generic process improvement approach, PDCA, can confirm the general applicability of the structured knowledge on process design and evaluation.

6.3.3. Business Activity and Information System

Developed business activity model can be re-usable for problems on risk-based decision making in general. **Figure 6-5** shows the business activity model for risk-based decision making supported by the five categorized knowledge on process design and evaluation, which is the reprint figure of **Figure 5-7**. This activity regards the external constraints as the strong factors to change the results and five categorized knowledge as the greatly supportive mechanisms to output the results. Because the differences of mechanisms are discussed in the previous sub-sections, the critical differences are the external constraints. This means that there is no difference of the framework of business activity model on the industry-specific conditions. Only the instances of concepts might be changed with such conditions.

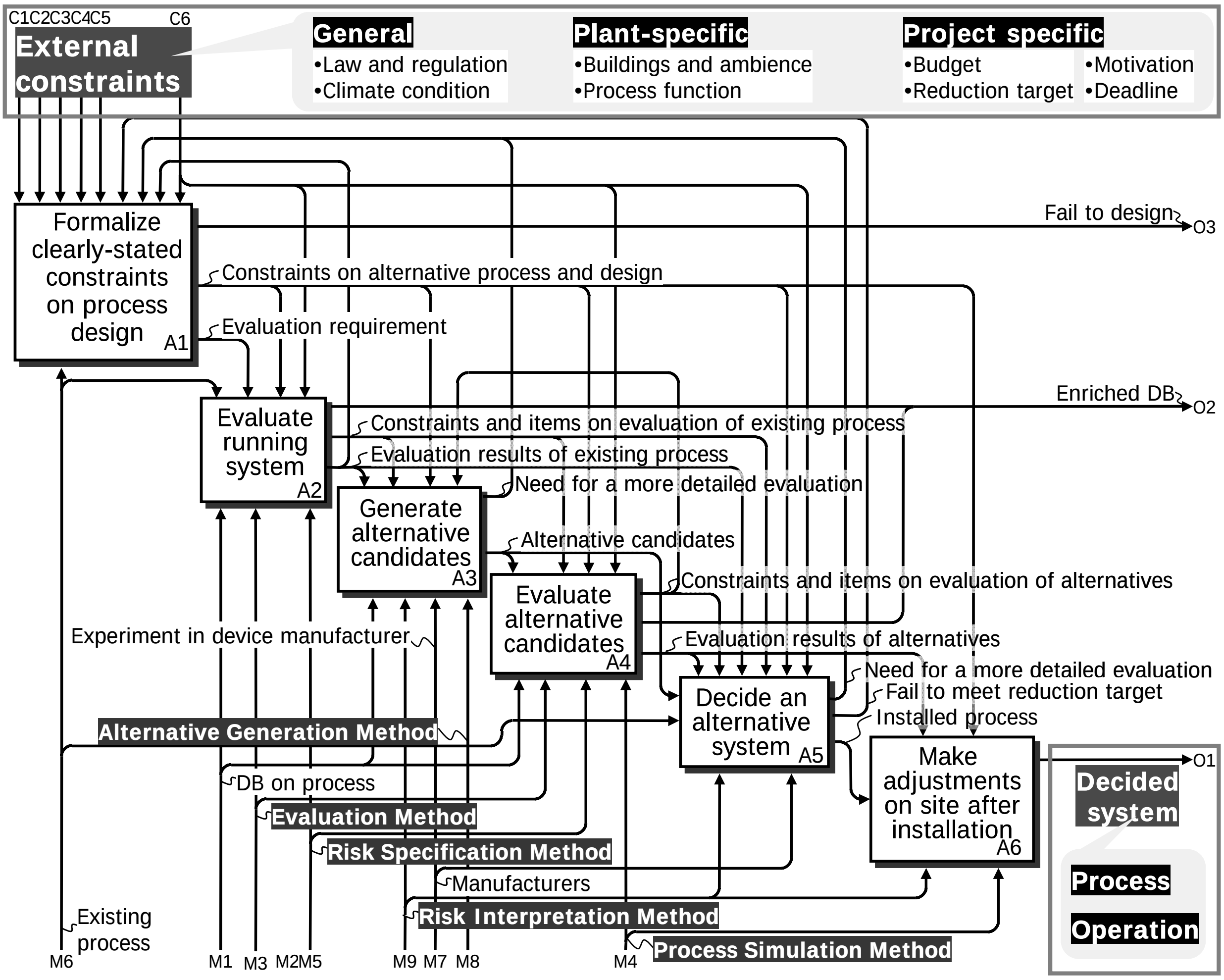


Figure 6-5 Business activity model of risk-based process design with five structured knowledge on design and evaluation (reprint of **Figure 5-7**)

External constraints are strongly dependent on the individual conditions of industry. For example on the process function, the SMEs managing metal cleaning process have no initiatives to change process function, while the chemical plant can make adjustments of it based on the marketing strategy. Other example should be mentioned on the project budget. Because chemical plants are usually managed by large enterprises, the budget of chemical plant design has a greater magnitude than that of metal cleaning process design.

The business activities on evaluation activities (A2: evaluate running process and A4: evaluate alternative candidates) has also similar structure among risk-based problems. **Figure 6-6** shows the evaluation activity structure for general problems. The evaluation indices must be specified on the industry-specific conditions on chemical usage, and the social sense of value, which could be formalized into the constraints on alternative process and design. Based on the specified evaluation indices, the sufficient assessment methodologies are selected and executed from A22 (A42) to A2n (A4n) as shown in **Figure 6-6**. A22, A23, and A24 are LCA, plant-specific RA, and feasibility assessment in metal cleaning process design.

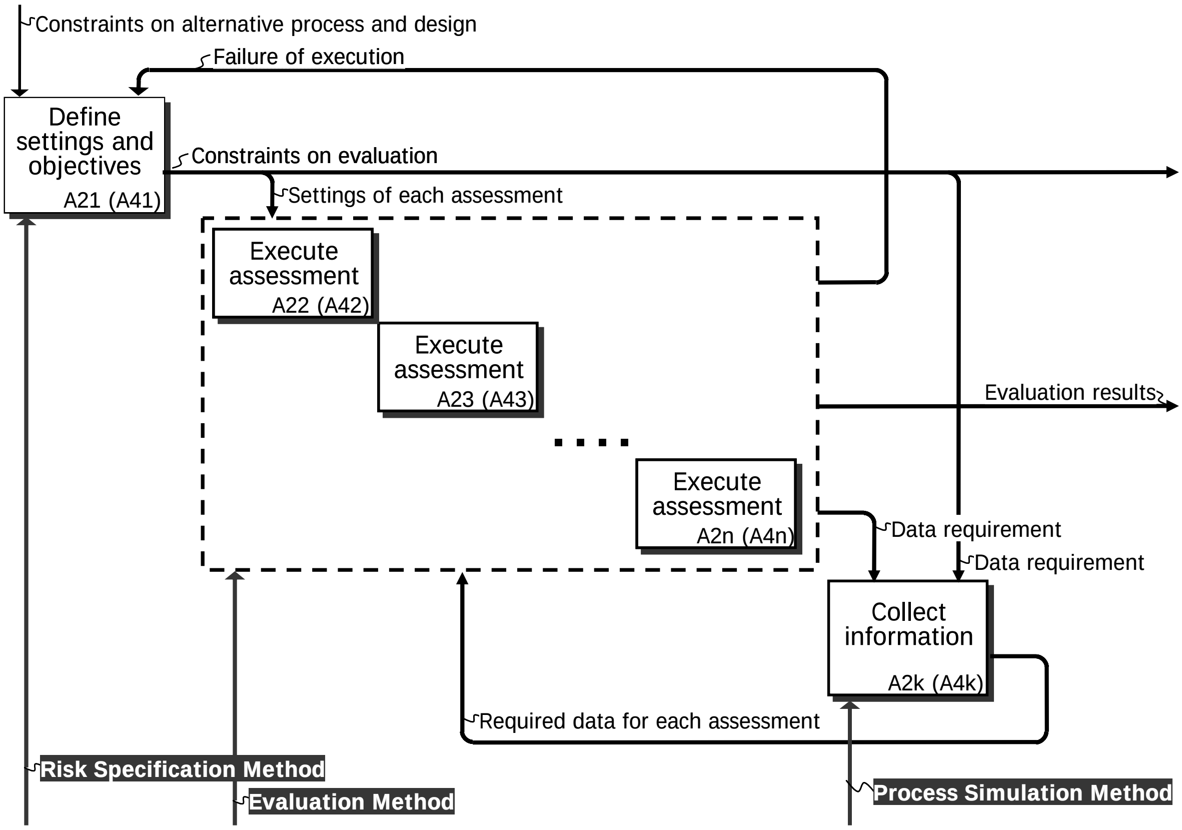


Figure 6-6 Evaluation activity for risk-based decision making in general

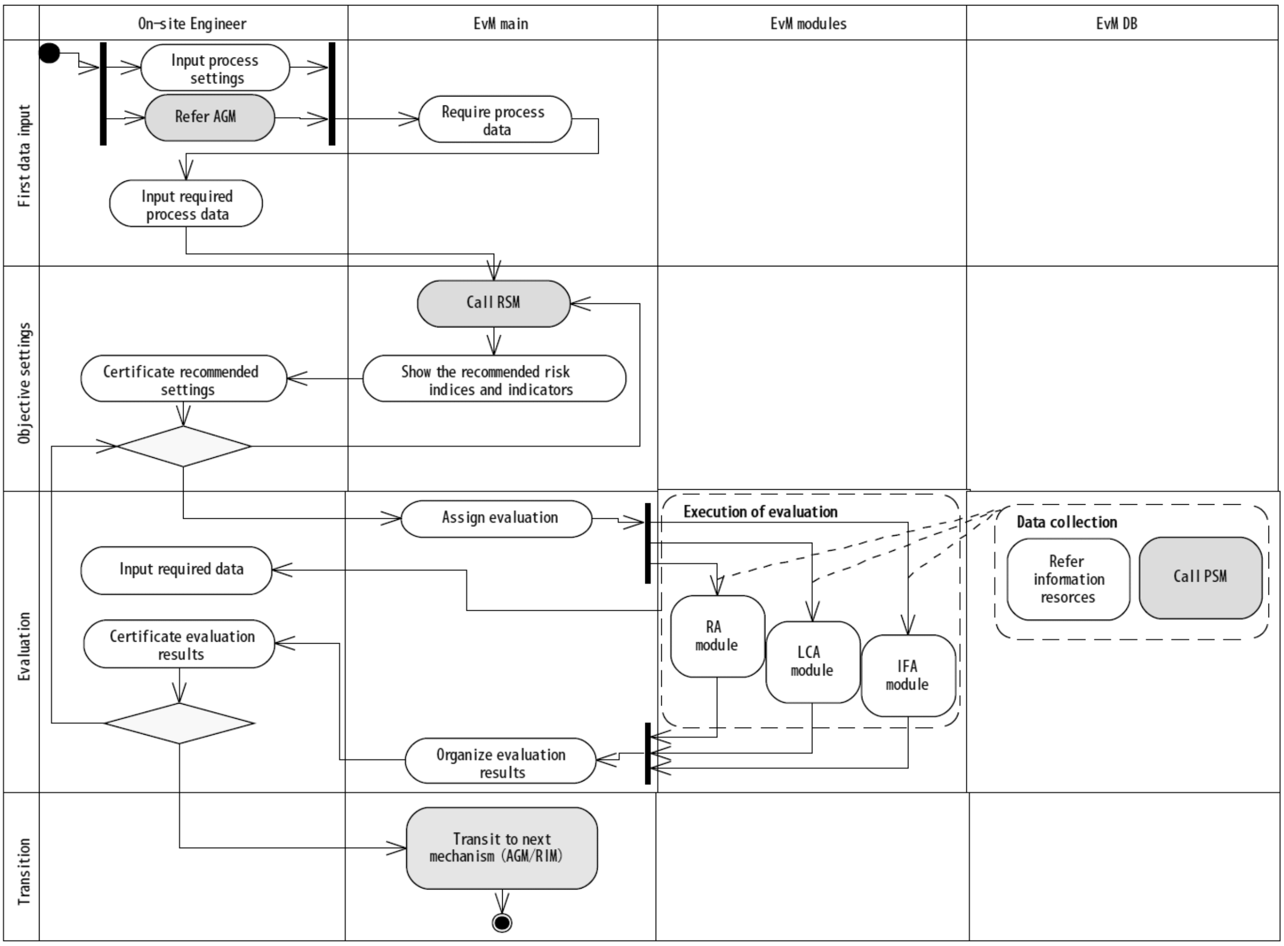


Figure 6-7 Activity relationship based on evaluation method in metal cleaning process design (reprint of **Figure 5-17**)

As well as the business activity model in evaluation, the software information system has also same structure among problems. **Figure 6-7** shows the activity relationship based on evaluation method in metal cleaning process design, which is the reprint of **Figure 5-17**. The phase of evaluation by EvM modules may be changed on the assessment methodologies selected in the activity A21 (A41) in **Figure 6-6**. At the same time, the PSM called in the data collection phase during execution of evaluation might be revised for estimating the data required for assessments. The colored activities are the connecting activity between other methods of five categorized knowledge. Although the instances of each method might be changed, the framework of the modules in software information system is not changed.

Business activity and software information system must be dependent on the knowledge structured for solving risk-based problems. The confirmation that the structured knowledge has the same structure means the framework of required activity and information can also be represented in the same structure. Of course, the instance knowledge on process design and evaluation should be developed on individual conditions, for example, the engineering databases for alternative generation. This research provides the templates of knowledge, which can be supportive information for the researchers of knowledge structuration.

6.4. Conclusion

This chapter verifies and validates the knowledge structuration proposed in this thesis. The proposed structured knowledge on process design and evaluation includes the existing concept for process improvement, PDCA cycle. The fifth systematized knowledge missed in PDCA cycle is the risk specification method, which can address the transition of objective functions to be evaluated in process design.

The effective and appropriate implementation of scientific knowledge into practice needs the assignments of modeling activities to researchers. In order to involve researchers in the integration and activation of developed scientific knowledge, the business activity and information system modelings should be practicable to them. At the publication phase of researches, their fruits should be represented as such models as well, for stimulating the actual implementation by system engineers.

Knowledge structuration can address the problems on risk-based decision making in a life cycle. For making it more effective, strategic problem identification must be conducted based on the proposed template. Based on the results of problem identification, other templates on knowledge structure, business activity, and software information system enable the scenario-based selection of engineering and scientific knowledge and technology on process design and evaluation.

Chapter 7. Conclusions and Recommendations for Future Studies

7.1. Conclusions

This dissertation presented the structuration of knowledge on process design and evaluation for risk-based decision making through logical considerations of combining knowledge originating from different research field. Knowledge structuration was defined in this dissertation as five conversion concepts of knowledge: experience and experiment, reasoning analysis, association, extended association, integration with activity, and activation by mechanism. Although the activities from generation to association have been generally performed in science and engineering, the last three require systematic approach to combine and connect logic on concepts in different field and have not been achieved adequately. To solve actual problem on risk-based decision making, knowledge including heuristics and theory on physicochemistry should be applied to establish novel practical knowledge structure enabling effective and viable trouble shooting. This knowledge structuration was demonstrated in actual case study of the risk-based design of metal cleaning process.

A method of associating LCA and RA into decision making was developed for process evaluation. These methodologies can evaluate different non-monetary aspects of decision making on the basis of similar information collection. The meanings of indicators in LCA and RA were carefully analyzed. The main difference of them is the temporal and spatial aspects of evaluated risks. RA can evaluate an immediate threat for a decision maker such as occupational health and safety risk. On the other hand, LCA can evaluate the regional/global impact through the life cycle of products. From the viewpoint of an on-site engineer, local risk should be evaluated in detail and interpreted more intensively than global impacts. Such difference between plant-specific RA and LCA originates from the technical data used for effect assessment. By specifying the plant, decision maker and exposed humans, plant-specific RA can utilize the detailed process data, such as the measured workplace concentrations and local conditions in the ambient surroundings, as well as the inventory data normally used for an ordinary LCA. From such detailed process data, plant-specific RA can evaluate local risk occurring in a situation more actual than that of an ordinary LCA. Due to the difference in motivation between local and global impact assessments, these impacts should be treated separately, but simultaneously. On the other hand, there are needs to integrate local and global impacts, for example, in evaluations for policy making. Based on the objectives of assessment and decision making, the knowledge on process evaluation should be connected with design activities.

For appropriate and effective utilization of different assessment methodologies, risk specification method for selecting risk indices and indicators was proposed on the basis of scientifically- and practically-validated logic. The algorithm of risk specification includes the consideration of hazardous properties, risk indices, indicators, and available technical data. Additionally, the attributions of risk indices and indicators were specified as the temporal and spatial aspects, to associate the knowledge on assessment. These enable the comprehensive consideration of risk occurred by decision. At the screening of risk indices and indicators, decision-maker should specify possibly better ones on scientific meaning. This thesis also discussed the recommendation method for adequate evaluation. The recommendation level was divided into physical exactitude, accuracy, and practicability. The scoring rules of them were decided to be able to compare existing evaluation indicators. Actual analyses of recommendation of existing evaluation indicators were performed on local risk in own process and other process, regionalization of environmental impacts, and aggregation of human health impacts originated in different impacts. The results could demonstrate the benefits of proposed recommendation level, which distinguish and rank available indicators.

For alternative generation and evaluation based on the evaluation results of process in use, the requirements of process models were defined, and they were developed through reasoning and associating the evidences from experiments by actual industrial machine and CFD analysis. For risk-based generation of alternative candidates, a physical linkage model was proposed. This model can reveal the physicochemical and mechanical relationship between process system parameters and function/risk. Based on the revealed logical relationship, alternative parameters can be assumed to reduce targeted risk with keeping enough process system function. Obtained knowledge on process behavior was stored as decision tables for alternative generation. The algorithm utilizes such decision tables was proposed. They can be the reservoir of associating the formalized knowledge on process.

Based on the needs from evaluation methodologies and alternative generation, quantifying process models developed by physical analysis was addressed and executed for industrial cleaning processes. Dominant risk factors and process parameters to them can be specified by the contribution analysis on evaluation results of process in use and the investigations on empirical knowledge, respectively. Based on the specified information, physical phenomena occurred in process should be grasped by utilizing all available mechanisms. CFD analysis has a large potential to visualize and understand important fluid dynamics in open-system process modeling. At the same time, experiments can indicate powerful mathematical facts on the relationship between process parameters and physical phenomena. In this regard, however, the empirical knowledge is useful to make effective plans of experiments, especially in open-system modeling. Because an evaluation should include the occupational and neighborhood risks around all processes in a life cycle, local concentrations must be estimated by using emission volumes. At that time, the uncertainties of estimations become a critical factor of miscalculation, because local risks are considerably sensitive to process data. For such highly uncertain modeling, statistical approaches can indicate compromised mathematical models. In this time, empirical knowledge should be implemented into the specification of parameters, because there can be lots of data doubtful as one dominating risk factors.

The way of interpreting evaluation results has two approaches, absolutely understanding the physical meanings of risk indices and indicators, and relatively comparing the evaluation results of alternative decisions. Both are available in risk-based decision making, and knowledge utilized in risk specification can be useful resources. Local risk visualized by RA should be judged whether they are acceptable, because such risk indices are sometimes critical for decision makers. On the other hand, global impact has often big uncertainty to understand quantitatively the physical meaning, because some impact categories are assumed that they occurs in several decades after emission. For such results, comparative decision making is applicable for easy interpretation with optional methods such as grouping, normalization, and weighting.

Risk specification, evaluation, risk-based alternative generation, process simulation, and interpretation can be essential steps for appropriate decision making considering risk. The knowledge and method of them were connected and defined as the structure of mechanism for risk-based decision making, which was derived from the structuration of knowledge on process design and evaluation. The interaction of each method was analyzed and implemented into a business model visualized by IDEF0 function modeling language. In this model, the integrated procedure of process evaluation and information flows among five mechanisms can be clearly defined. At the same time, the information system models required for the activation of risk-based decision making can be discussed and modeled by IDEF1x and UML information modeling languages. IDEF1x can link to the development of databases cumulating knowledge on process design and evaluation. UML can define the requirements of software information system activating risk-based decision making. The combination of these modeling languages can visualize the achievements of knowledge structuration.

The general applicability of proposed structured knowledge on process design and evaluation was verified by discussion on the inclusion of them into the existing concept for process improvement. The visualization of activity and information has an important role of making a consensus on sustainable BPR implementing such scientific knowledge. IDEF0 can play a role to identify the activity relation including small and detail and other viewpoints. IDEF1x and UML enable the detail discussion on the supporting mechanisms, which are inevitable for actual implementation of risk-based decision making. For making it more effective, the template of strategic problem identification was developed. Based on the results of the problem identification, other developed templates on knowledge structure, business activity, and software information system enabled the scenario-based selection of engineering and scientific knowledge and technology on process design and evaluation.

In summary, this thesis proposes the templates of discussing such implementation of knowledge as well as appropriate structured knowledge on process design and evaluation. The pentagonal knowledge structure and its business activity and supporting software system models are the scenario-based framework of applying engineering and scientific knowledge into practice in risk-based decision making. It can be a strong mile stone for the knowledge structuration implementing distributed knowledge, skill, technology, and heuristics into practice for improving decision making for sustainable future.

7.2. Recommendations for Future Studies

This thesis can generate the following recommendations for future studies.

Improvement of Method to Specify Risk Indices on Process Information

Actual decision makers have difficulties to specify risk indices and indicators. This thesis proposed the algorithm of specifying the risk indices and indicators through the consideration of all possible items. This approach can be activated by databases on chemical risks with the supporting information of the difference of items such as temporally and spatially aspects of them. In this regard, however, the decision must be more practical on the possibility and recommendation of each item, especially of risk index.

Risk indices can be infinitely increased on the hazardous properties. The existences of explosion limits in the hazardous properties of chlorinated solvents are the examples. However, the physical risks by such properties have been hardly reported in metal cleaning processes. This is because they are utilized as cleansing agent in washing machines, where the conditions cannot be suitable for explosion.

A general method to specify risk indices based on such possible process conditions can be useful for risk controls of chemicals in specific industries. For the development of this method, the databases on the conditions in processes utilizing chemical substances, the previous accidents, and the results of risk evaluation.

Enhancement of Risk Evaluation and Interpretation of EHS Risk Categories

For evaluation and comparison of EHS risks, the individual evaluation methods for each risk and the comparative methods must be practicable. By the substitution of chemical substances, risk-trade off might be caused among EHS categories. Because the behavior and management styles of risks are completely different, the quantitative comparison cannot be performed simply.

One of the assessment methods on different categories can be EHS method (Koller 2000; Koller et al. 2000, 2001). The result of EHS method for chemical substances possibly included in cleansing agents is shown in **Figure 7-1**. Because this assessment is completely based on the hazardous properties of chemicals, the mass, concentration, and conditions of the usage of chemical substances cannot be considered adequately. For risk evaluation, several information is needed as organized in **Table 7-1**. Such information is not always available for decision makers, and the lack of it can be a bottleneck of decreasing the practicability of total EHS risk assessment.

To improve the actual situation of risk management, the method should be fixed for risk evaluation of EHS categories. At the same time, the comparative method must be developed. Through these researches, the requirements of information, mechanisms, and activities can be defined as shown in this thesis. Effective databases might be established based on them.

Algorithmic Improvement for Automation of Alternative Generation

The automation of alternative generation can be achieved by the algorithm proposed in this thesis. In the method, decision tables have the largest roles of generating alternatives. In this regard, the developments of such decision tables cannot be automated. The way of developing the tables has not also been developed. For the completely generalized automation of alternative generation, the logics of developing the decision tables and the algorithm should be discussed and established with actual case studies on other process developments. It should include not only industrial process design, but also policy making and recycle system design by local governments. Through these researches, technologies on alternative generation and its supports can be systematized and available for knowledge structuration.

Expansion of Risk-Based Decision Making toward Comprehensive Risk Control

Chemical substances are applied in all processes including industrial and consumers activities for achieving required functions. They are inevitable components in activities, and there is no substitution for some of them. At the same time, all chemical substances have hazardous properties and cause chemical risk of EHS categories. With regard to the utilization of chemical substances for the achievements of functions, risk due to the use of them must be acceptable, otherwise the achieved function cannot be practicable. Risk-based decision making in this thesis needs risk specification, evaluation, and generation of alternatives. Such decision making method has the potential to tackle the comprehensive risk control problems. To reveal the inevitable risk for achieving specific functions, not only parameter-risk and parameter-function, but also risk-function analysis must be implemented in the knowledge structuration for risk-based decision making.

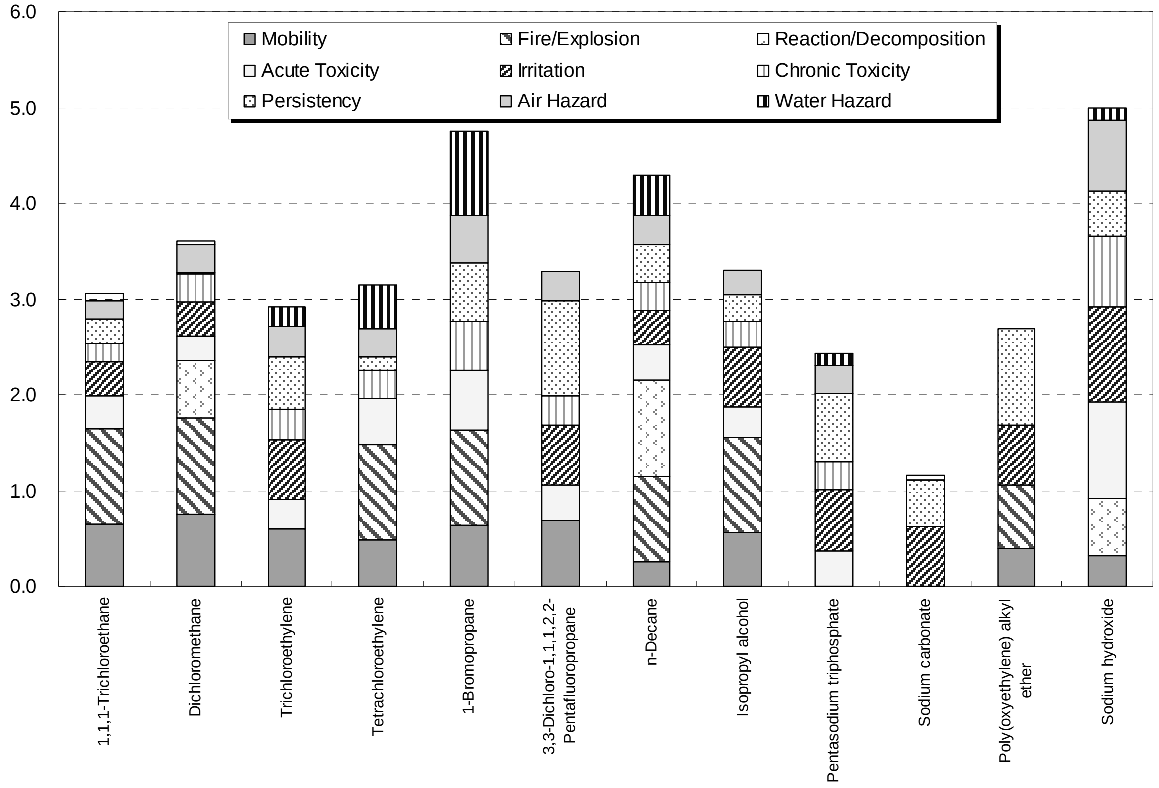


Figure 7-1 Hazard assessment results on the basis of EHS methods

Table 7-1 Required data and models to evaluate actual emission source-specific risks

EHS category	Analysis	Required data	Required information or model
Health	Continuous exposure analysis	Concentration in working place	Dispersion model in the indoor environment
			Emission volume into the indoor environment
			Dimensions of working place
			Physical conditions (temperature, moisture)
			Air exchange rate
		Concentration in ambient surroundings	Dispersion model in the ambient surroundings
			Emission volume into the environment
			Climate
			Population density
			Position of exhaust port
	Accidental exposure analysis	Total amount of dermal contact	Working sequence
			Working method
			Use conditions
			Working conditions
			Frequency of hazardous work
Safety	Semi quantitative analysis		Frequency of hazardous work
			Degree of hazard caused by each hazardous work
	Quantitative analysis		Possibility of each failure mode

Further Application of Knowledge Structuration Involving Supply Chain

A supply chain of product involves many kinds of decision making. In such decision making, constraints and functions of processes are interactively related each other. At the same time, the victims and factors of risk can be located in different life cycle stakeholders, for example, the selection of raw material can cause product risks in consumption phase of product. In this case, however, the decision by consumers can be a dominant risk factor.

The decision making and risk have considerably complicated relationship, and it is often beyond the decidable range of a decision maker. To reduce the risk attributable to the use of chemical, life cycle risk assessment (LCRA) and optimization must be considered in LCM. There are several potential researches for LCRA such as the integrated application of scenario-based RA and LCA by multiple decision makers. Theses approaches should be discussed on actual case studies including all kinds of decision making in a supply chain, which include policy making although it is not a part of supply chain.

Life cycle, or supply chain is composed of multiple decision-makers, who have different decidable ranges and objective functions. At that time, they make decisions on life-cycle design parameters within their own decidable ranges. Life cycle can be regarded as a process system composed of such parameters. The remarkable feature of life-cycle design parameters is that it can be constraints of other decision-makers in the life cycle explicitly and implicitly. Because those who design parameters are not same as those who are constrained, the implicit constraints cause misunderstandings and unnecessary change in the design parameters of other decision makers.

Figure 7-2 shows the possible patterns of constraining stakeholders. Category I means the own process design. Category II is the cells including process parameters affecting the previous or the following life cycle stages. The parameters mapped in category III can be regarded to have a significant potential to affect life cycle.

Figure 7-3 shows the life-cycle design parameters attributable to the stakeholders in life cycles. In the cells, life-cycle design parameters are mapped, which have possibility to be the factors of chemical risk around the decision makers in the first line. In each line, the designable parameters for the decision-makers in the first row are organized in the rows of stakeholders affected by the parameters. The diagonal cells mean the process parameters for each decision maker.

Structuration of knowledge can provide the understandings of the conditions of other decision makers, as well as the state-of-the-art methods converted into the practicable styles. It can effectively improve the decision making of existing life-cycle design parameters on the cells of **Figure 7-3**. Additionally, it has the possibilities to find out and establish novel relationships between stakeholders, which means the alignments of novel parameters on the cells of **Figure 7-3**.

Figure 7-4 shows LC-design parameters for risk-based decision making on value-added industry. In this problem, the anteroposterior processes in supply chain have the critical right of changing the decision making in value-added industries. **Figure 7-5** shows the LC-design parameters for risk-based decision making on additives in compound. The parameters in compound industries affect the downstream processes in supply chain, which are not next to the industries. It means that the design of such parameters should be based on scenario assessments considering the supply chain.

The problem identification is the essence to select, associate, and integrate the knowledge with business in supply chain. The strategic problem identification and classification of such problems on risk-based decision making should be considered with actual case study on the multi-stakeholder problems in a supply chain. Afterward, the structuration of knowledge for novel supply chain management should be discussed.

		Stakeholders under constraints		
		A	B	C
Stakeholders making decision	A	I	II	III
	B	II	I	II
	C	III	II	I

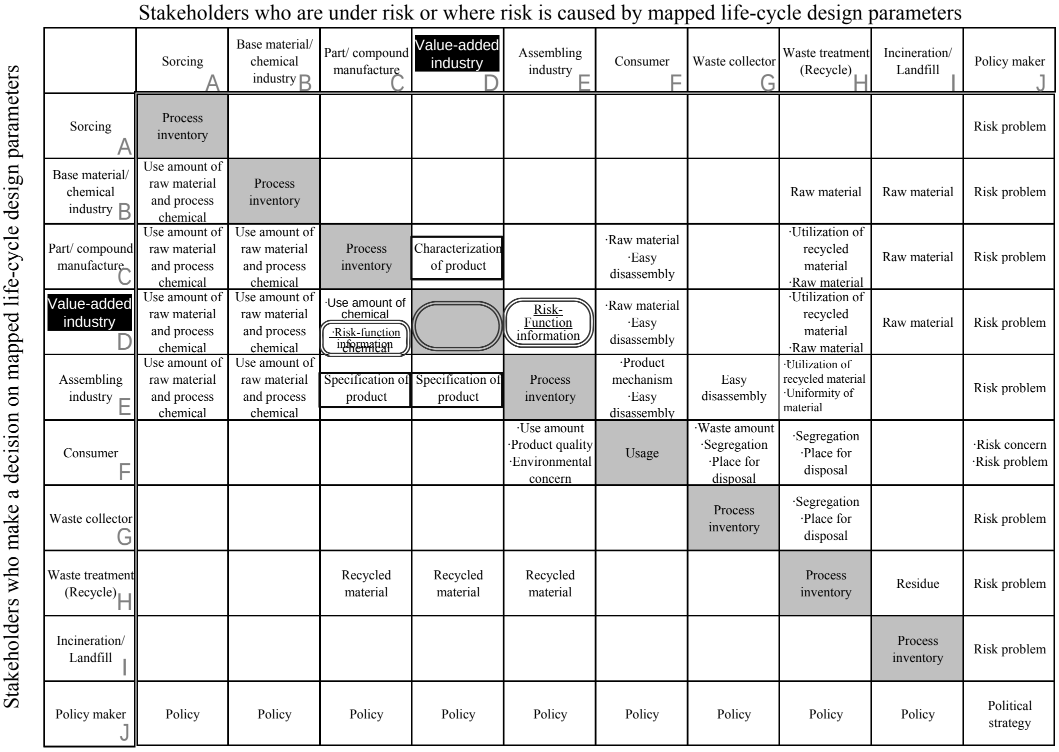
Figure 7-2 Problem identification matrix

Stakeholders who are under risk or where risk is caused by mapped life-cycle design parameters

Stakeholders who make a decision on mapped life-cycle design parameters

	Sorcing A	Base material/ chemical industry B	Part/ compound manufacture C	Value-added industry D	Assembling industry E	Consumer F	Waste collector G	Waste treatment (Recycle) H	Incineration/ Landfill I	Policy maker J
Sorcing A	Process inventory									Risk problem
Base material/ chemical industry B	Use amount of raw material and process chemical	Process inventory						Raw material	Raw material	Risk problem
Part/ compound manufacture C	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Process inventory	Characterization of product		·Raw material ·Easy disassembly		·Utilization of recycled material ·Raw material	Raw material	Risk problem
Value-added industry D	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Process inventory		·Raw material ·Easy disassembly		·Utilization of recycled material ·Raw material	Raw material	Risk problem
Assembling industry E	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Specification of product	Specification of product	Process inventory	·Product mechanism ·Easy disassembly	Easy disassembly	·Utilization of recycled material ·Uniformity of material		Risk problem
Consumer F					·Use amount ·Product quality ·Environmental concern	Usage	·Waste amount ·Segregation ·Place for disposal	·Segregation ·Place for disposal		·Risk concern ·Risk problem
Waste collector G							Process inventory	·Segregation ·Place for disposal		Risk problem
Waste treatment (Recycle) H			Recycled material	Recycled material	Recycled material			Process inventory	Residue	Risk problem
Incineration/ Landfill I									Process inventory	Risk problem
Policy maker J	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Political strategy

Figure 7-3 Life-cycle design parameters attributable to stakeholders: as-is matrix

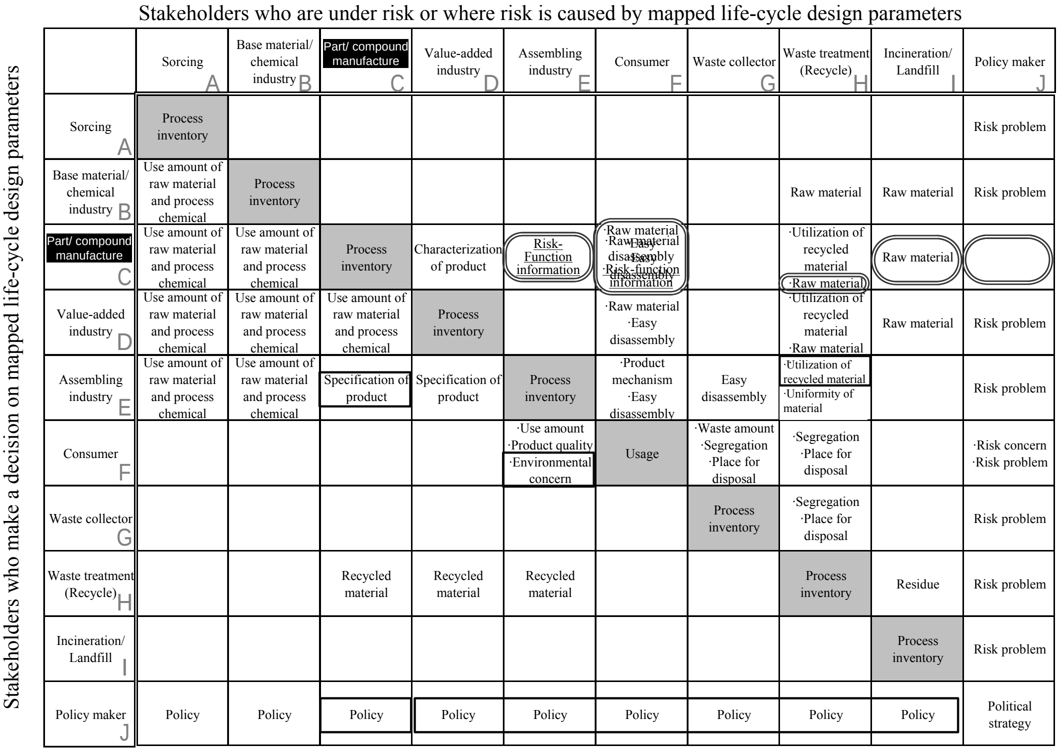


Stakeholders who are under risk or where risk is caused by mapped life-cycle design parameters

Stakeholders who make a decision on mapped life-cycle design parameters

	Sorcing A	Base material/ chemical industry B	Part/ compound manufacture C	Value-added industry D	Assembling industry E	Consumer F	Waste collector G	Waste treatment (Recycle) H	Incineration/ Landfill I	Policy maker J
Sorcing A	Process inventory									Risk problem
Base material/ chemical industry B	Use amount of raw material and process chemical	Process inventory						Raw material	Raw material	Risk problem
Part/ compound manufacture C	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Process inventory	Characterization of product		·Raw material ·Easy disassembly		·Utilization of recycled material ·Raw material	Raw material	Risk problem
Value-added industry D	Use amount of raw material and process chemical	Use amount of raw material and process chemical	·Use amount of chemical ·Risk-function information chemical		Risk-Function information	·Raw material ·Easy disassembly		·Utilization of recycled material ·Raw material	Raw material	Risk problem
Assembling industry E	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Specification of product	Specification of product	Process inventory	·Product mechanism ·Easy disassembly	Easy disassembly	·Utilization of recycled material ·Uniformity of material		Risk problem
Consumer F					·Use amount ·Product quality ·Environmental concern	Usage	·Waste amount ·Segregation ·Place for disposal	·Segregation ·Place for disposal		·Risk concern ·Risk problem
Waste collector G							Process inventory	·Segregation ·Place for disposal		Risk problem
Waste treatment (Recycle) H			Recycled material	Recycled material	Recycled material			Process inventory	Residue	Risk problem
Incineration/ Landfill I									Process inventory	Risk problem
Policy maker J	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Political strategy

Figure 7-4 LC-design parameters for risk-based decision making on value-added industry



Stakeholders who are under risk or where risk is caused by mapped life-cycle design parameters

Stakeholders who make a decision on mapped life-cycle design parameters

	Sorcing A	Base material/ chemical industry B	Part/ compound manufacture C	Value-added industry D	Assembling industry E	Consumer F	Waste collector G	Waste treatment (Recycle) H	Incineration/ Landfill I	Policy maker J
Sorcing A	Process inventory									Risk problem
Base material/ chemical industry B	Use amount of raw material and process chemical	Process inventory						Raw material	Raw material	Risk problem
Part/ compound manufacture C	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Process inventory	Characterization of product	Risk-Function information	·Raw material ·Easy disassembly ·Risk-function information		·Utilization of recycled material ·Raw material	Raw material	
Value-added industry D	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Process inventory		·Raw material ·Easy disassembly		·Utilization of recycled material ·Raw material	Raw material	Risk problem
Assembling industry E	Use amount of raw material and process chemical	Use amount of raw material and process chemical	Specification of product	Specification of product	Process inventory	·Product mechanism ·Easy disassembly	Easy disassembly	·Utilization of recycled material ·Uniformity of material		Risk problem
Consumer F					·Use amount ·Product quality ·Environmental concern	Usage	·Waste amount ·Segregation ·Place for disposal	·Segregation ·Place for disposal		·Risk concern ·Risk problem
Waste collector G							Process inventory	·Segregation ·Place for disposal		Risk problem
Waste treatment (Recycle) H			Recycled material	Recycled material	Recycled material			Process inventory	Residue	Risk problem
Incineration/ Landfill I									Process inventory	Risk problem
Policy maker J	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Policy	Political strategy

Figure 7-5 LC-design parameters for risk-based decision making on additives in compound

Abbreviation

ACGIH	American Conference of Governmental Industrial Hygienists
BPR	Business Process Re-engineering
BW	Body Weight
DALY	Disability Adjusted Life Years
DCM	Dichloromethane
DfE	Design for Environment
DFG	Deutsche Forschungsgemeinschaft
EHS	Environment, Health, and Safety
ERA	Environmental (Ecological) Risk Assessment
HC	Hydrocarbon
IARC	International Agency for Research on Cancer
IDEF	Integrated DEFinition
ISHL	Japan, Industrial Safety and Health Low
ISO	International Organization for Standardization
JICC	Japan Industrial Conference on Cleaning
JSOH	Japan Society for Occupational Health
LCA	Life Cycle Assessment
LCE	Life Cycle Engineering
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
LCRA	Life Cycle Risk Assessment
LIME	Life-cycle Impact assessment Method based on Endpoint modeling
LOAEL	Lowest Observed Adverse Effect Level
MAFF	Ministry of Agriculture, Forestry and Fisheries of Japan
METI	Ministry of Economy, Trade and Industry, Japan
MELW	Ministry of Health, Labour and Welfare, Japan
MOE	Margin of Exposure

MOEn	Ministry of the Environment, Japan
NEDO	New Energy and industrial technology Development Organization
$N_{exposed}$	the Number of exposed person
NOAEL	No Observed Adverse Effect Level
OMNIITOX	Operational Models aNd Information tools for Industrial applications of eco/TOXicological impact assessments
OPOSP	Ordinance on Prevention of Organic Solvent Poisoning
PDI	Predicted Daily Intake
PRTR	Pollutant Release and Transfer Register
PSE	Process Systems Engineering
QSHA	Occupational Safety and Health Administration
RA	Risk Assessment
RfD	Reference Dose
SDK	Software Development Kit
SETAC	Society of Environmental Toxicology and Chemistry
SMEs	Small- and Medium-sized Enterprises
1,1,1-TCE	1,1,1-Trichloroethane
TCE	Trichloroethylene
TLV	Threshold Limit Value
TWA	Time-Weighted Average
UFs	Uncertainty Factors of NOAEL
UML	Unified Modeling Language
UNEP	UN Environment Programme
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds

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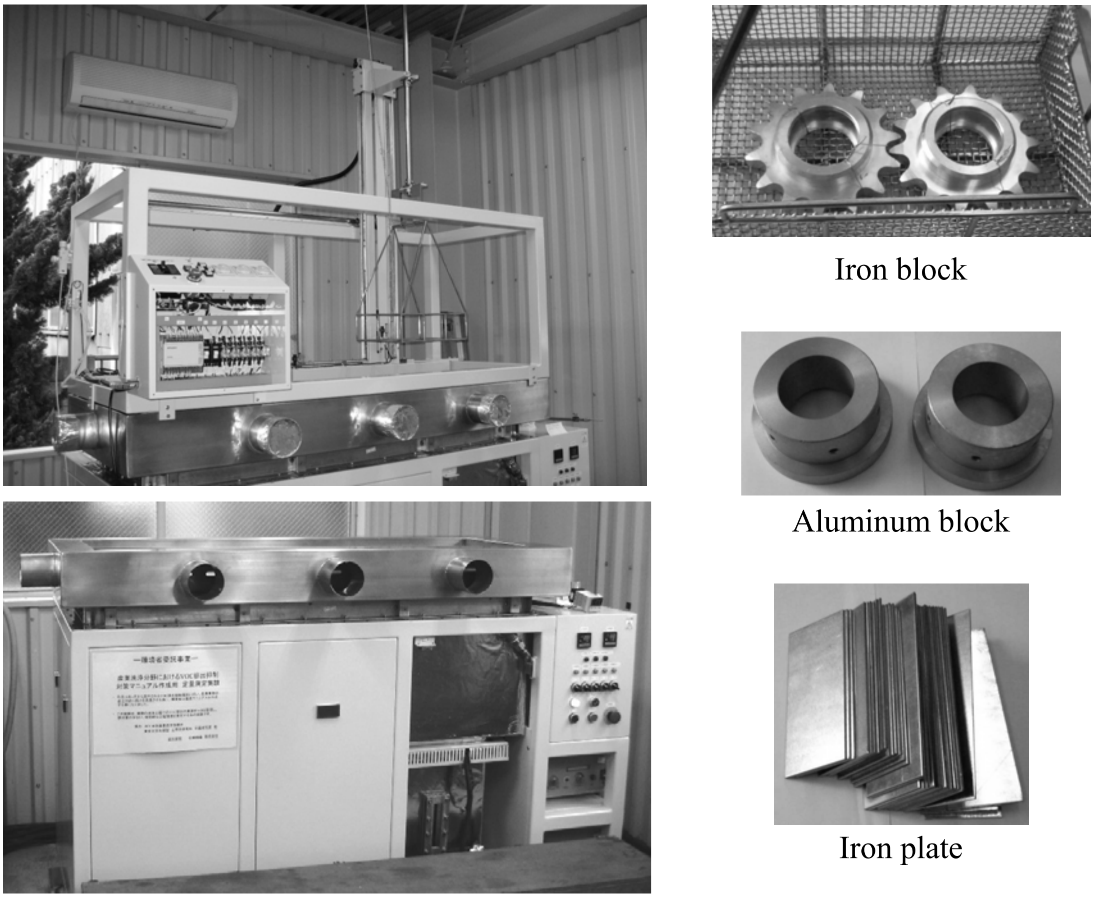
Supporting Information

Appendix – A: Process Analysis of Metal Cleaning Process

This appendix includes the parts of the method and the result of evidence collection for process modeling. It includes experiments and CFD analysis. A-1 shows the experimental settings. The physicochemical analysis results are demonstrated in A-2. The results of CFD analysis are partly shown in A-3.

A – 1: Experiments with Industrial Machine

In this thesis, the experiments were conducted on industrial metal cleaning processes with a great deal of cooperation by industries and JICC. Two industrial washing machines were available for the experiments.



Iron block

Aluminum block

Iron plate

Figure A-1 Industrial cleaning machine 1 for experiment

Table A-1 Specification of cleaning machine 1 for experiment [mm]

	Height	Width	Depth
Washing bath	350	370	340
Rinsing bath	380	370	340
Vapor washing bath	-	370	340
Vapor zone	520	1360	420
External size	1210	1940	950

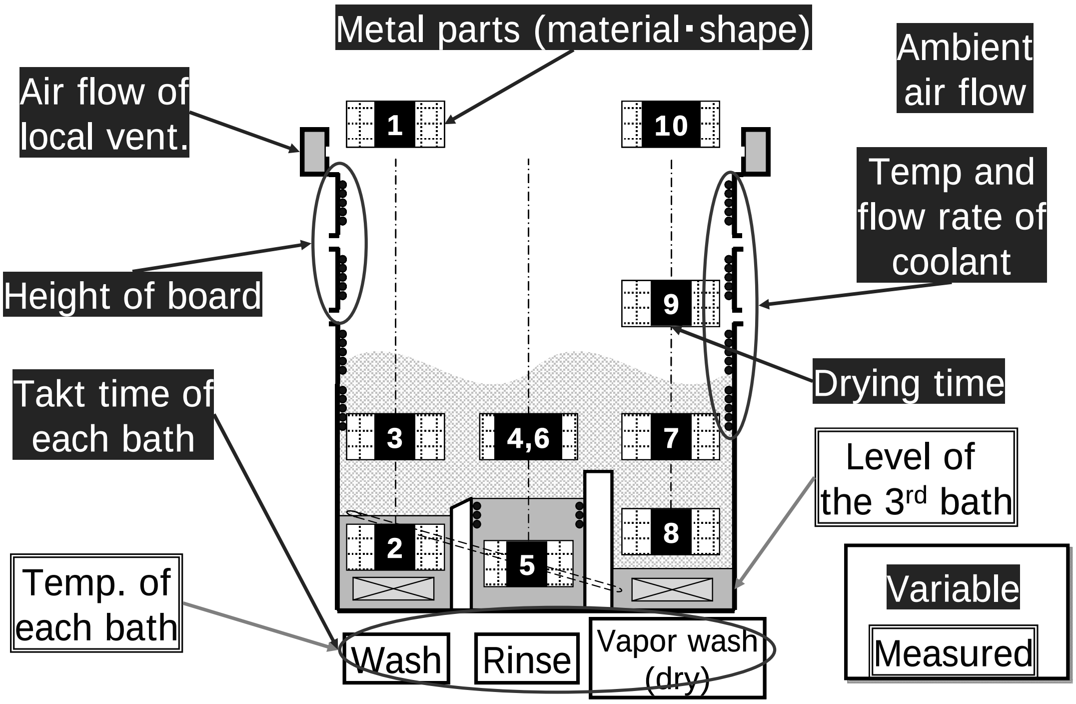


Figure A-2 Experimental parameters in industrial washing machine B

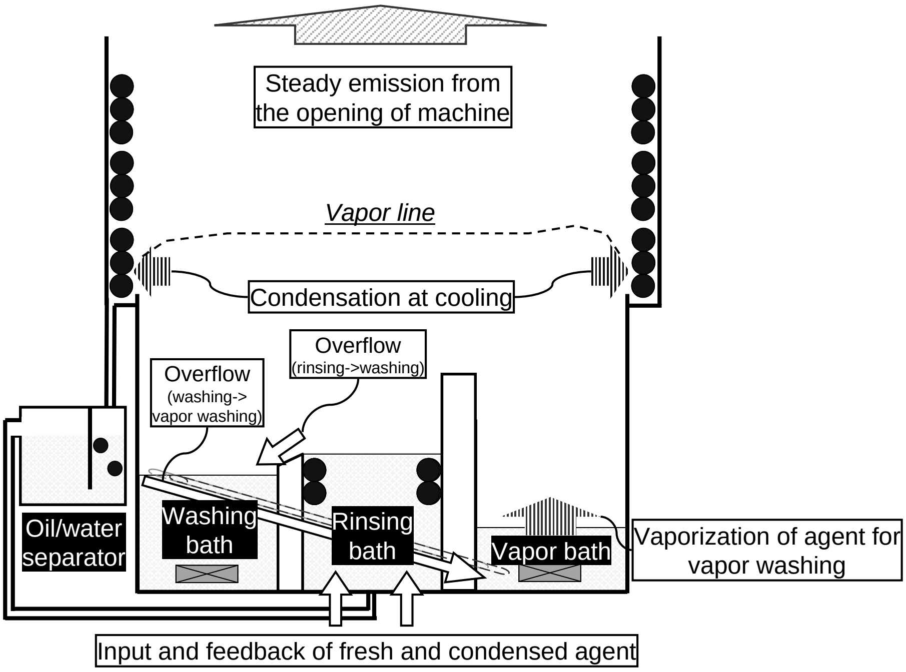
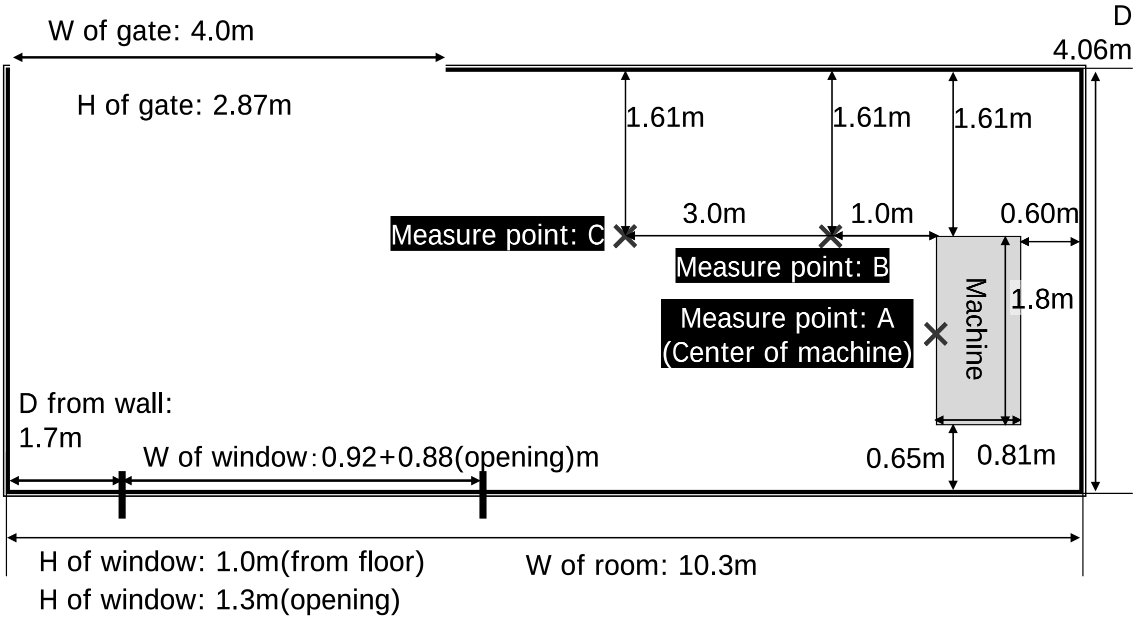
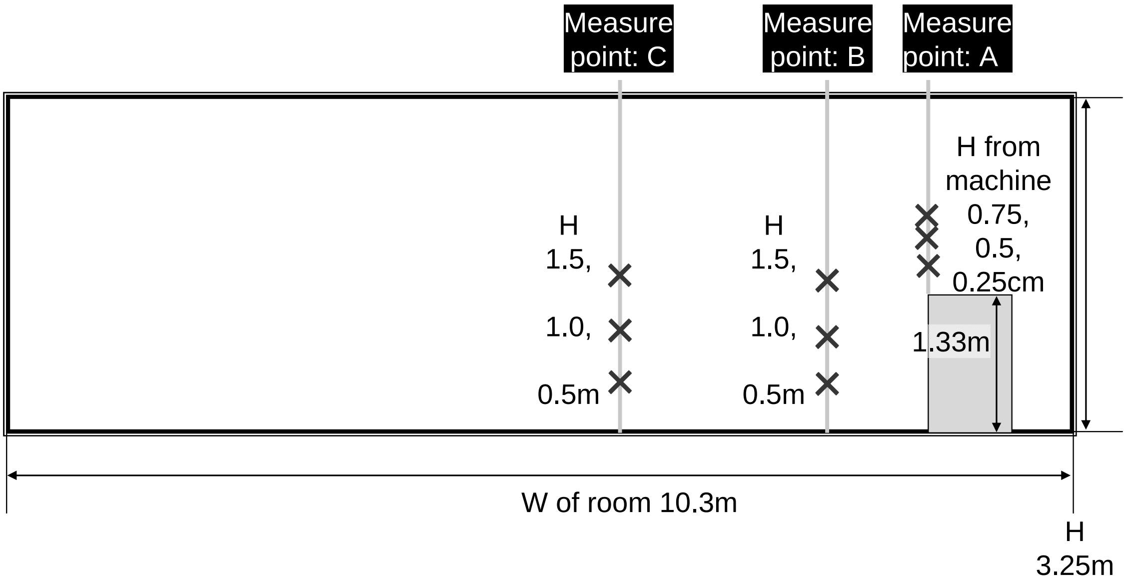


Figure A-3 Basic agent cycle inside of cleaning machine



(a) Vertical direction



(b) Crosswise direction

Figure A-4 Layout of the experimental room in industry and measure points for concentration of cleansing agent

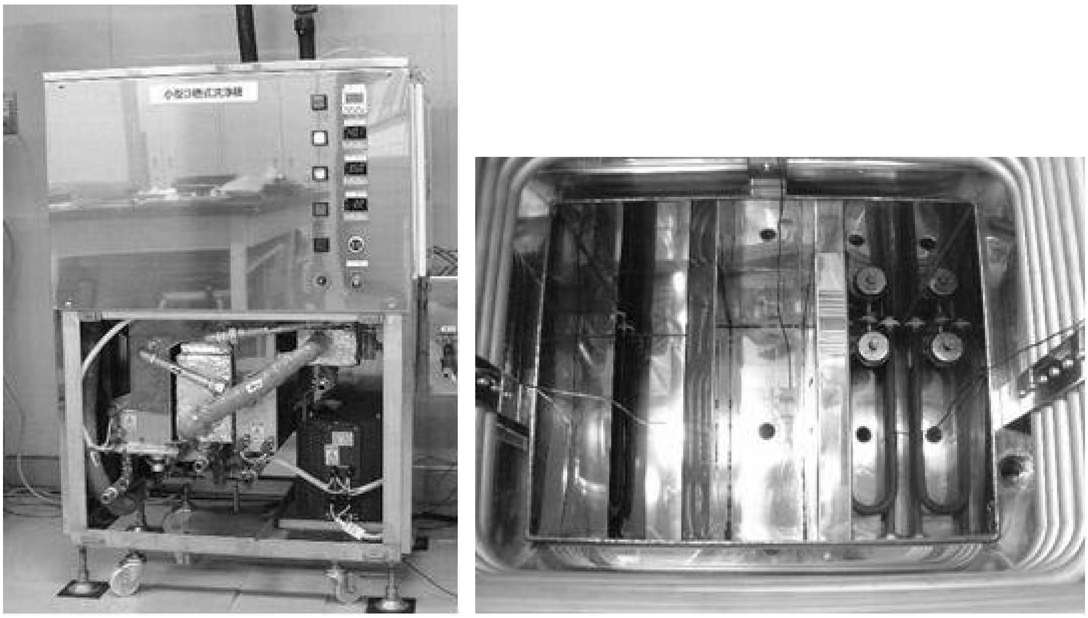


Figure A-5 Industrial cleaning machine 2 for experiment

Table A-2 Specification of cleaning machine 2 for experiment [mm]

	Height	Width	Depth
Washing bath	210	90	260
Rinsing bath	210	90	260
Vapor washing bath	-	90	260
Vapor zone	430	425	350

A – 2: Physicochemical Analysis

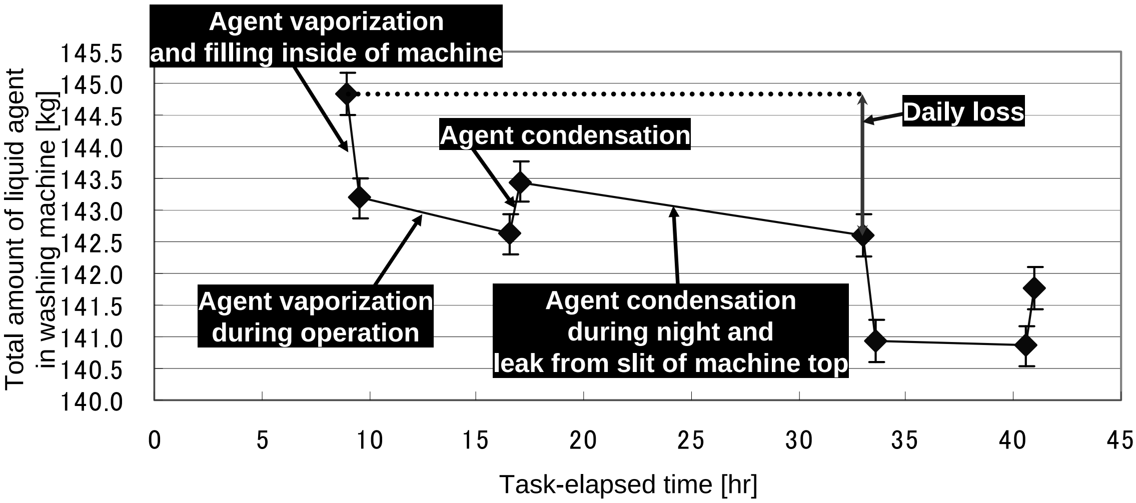


Figure A-6 Daily change of the total amount of liquid agent in washing machine

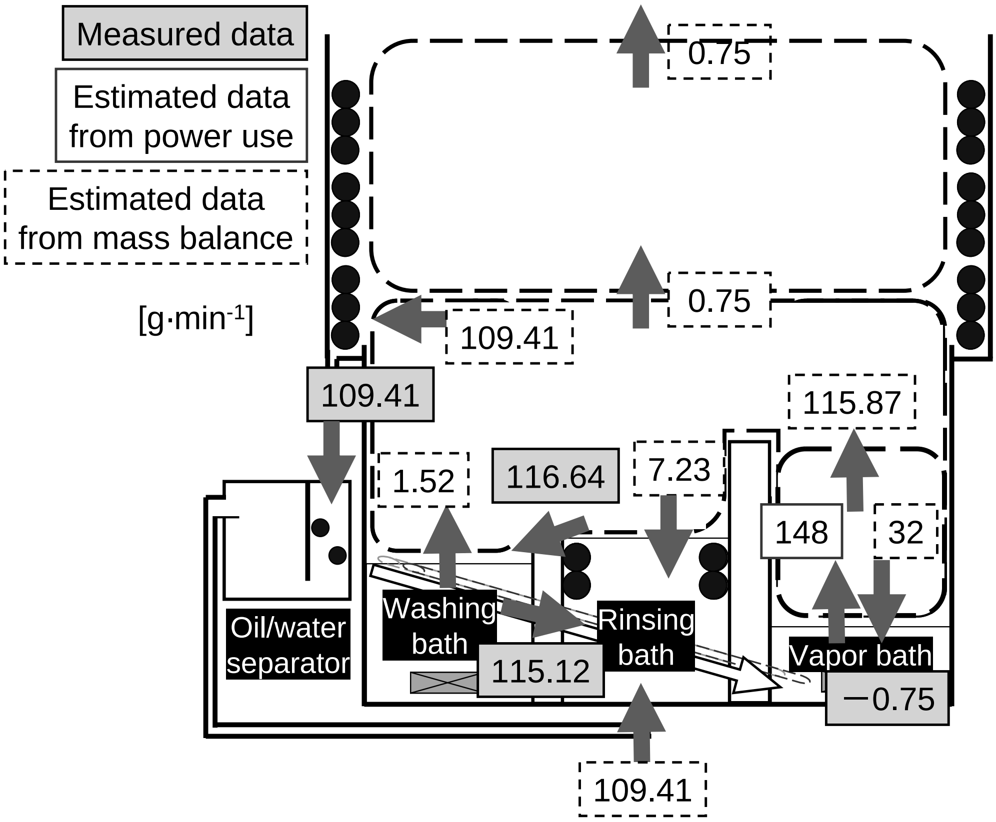
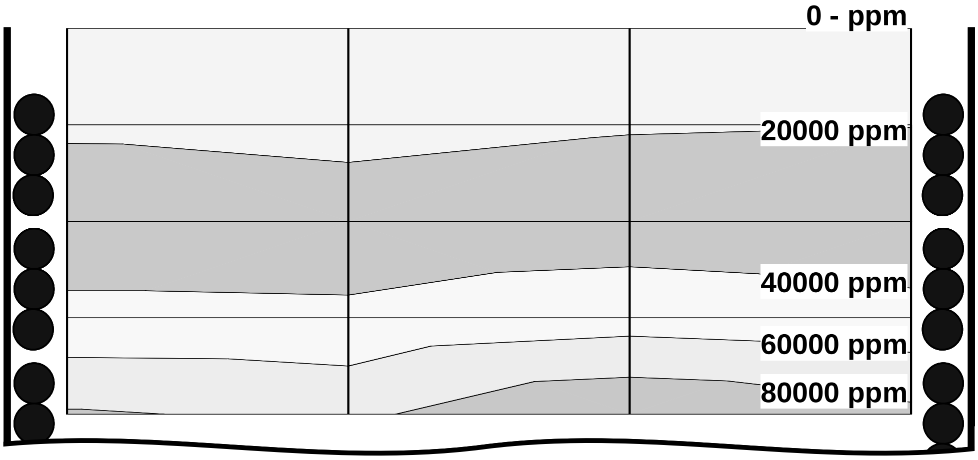
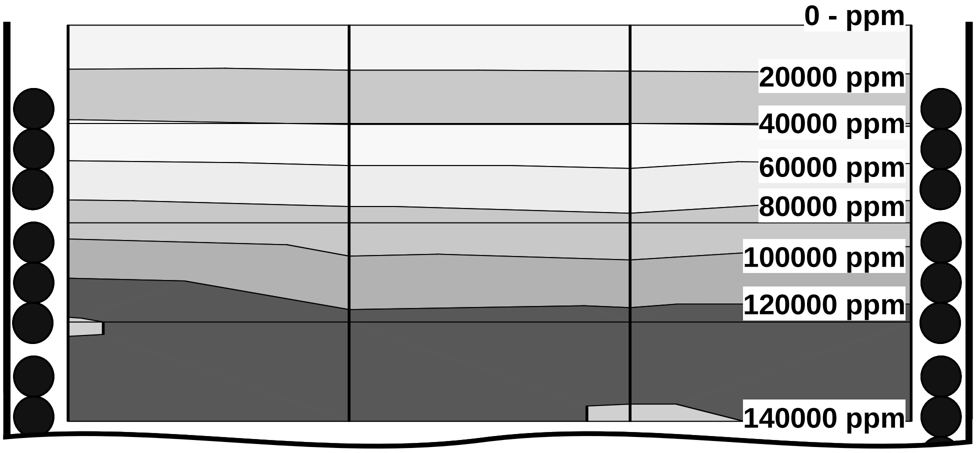


Figure A-7 Material flows inside of washing machine during operation

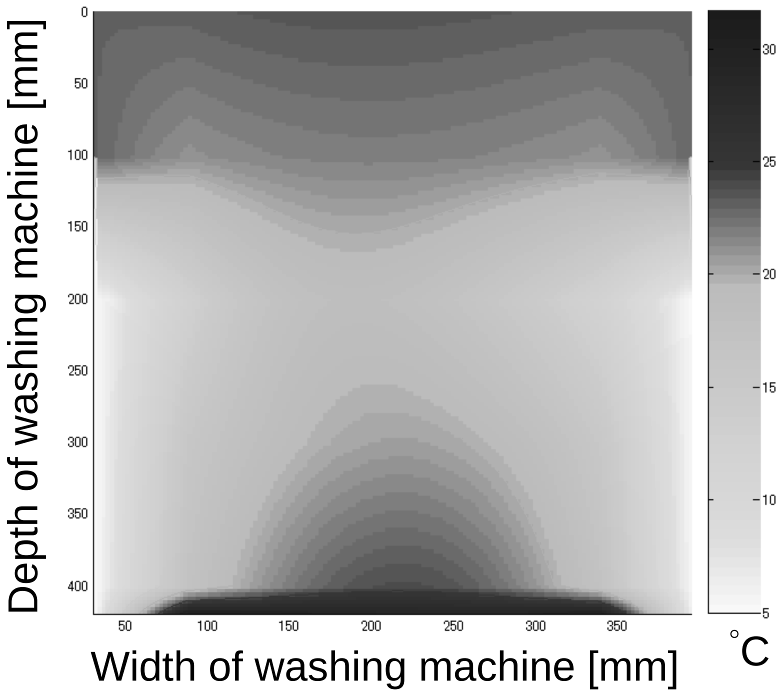


(a) T_{cool}: 5 deg C

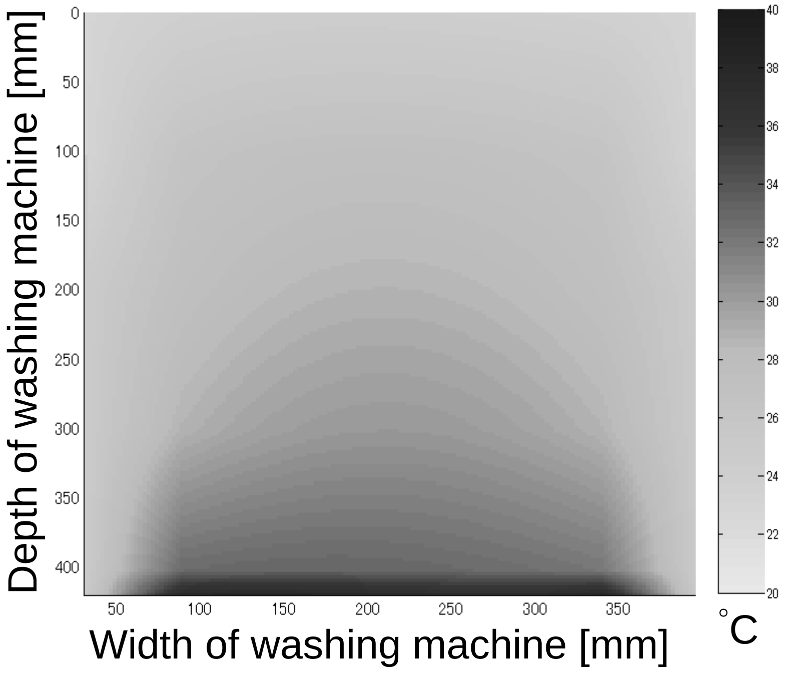


(b) T_{cool}: 25 deg C

Figure A-8 Measured concentration distribution inside of machine



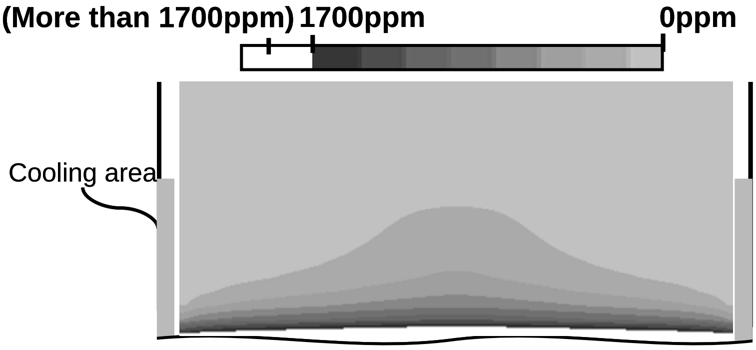
(a) T_{cool}: 5 deg C



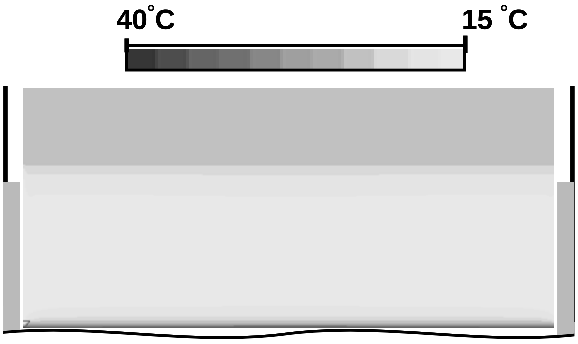
(a) T_{cool}: 25 deg C

Figure A-9 Measured temperature distribution inside of machine

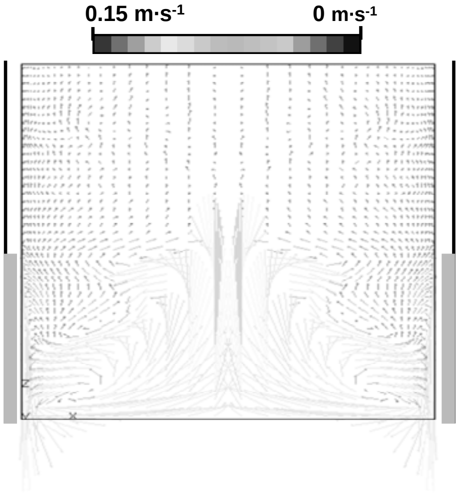
A – 3: Computational Fluid Dynamics Analysis



(a) Concentration distribution



(b) Temperature distribution



(c) Air flow vector

Figure A-10 CFD results on inside of washing machine

Appendix – B: Overviews of IDEF and UML

IDEF and UML are the ones of the modeling languages for system management and development in engineering, manufacturing, and other all organizations. IDEF family is organized in **Table B-1** and its application into BPR is illustrated in **Figure B-1**. Software development life cycle is organized in **Table B-2** and UML diagrams are organized in **Table B-3**. **Table B-3** also simply indicates the logical reason why some diagrams should be constructed by researchers.

Table B-1 Functional diagrams standardized as IDEF family (KBSI 1993)

IDEF diagrams		Content
IDEF0	Function modeling	The IDEF0 Function Modeling method is designed to model the decisions, actions, and activities of an organization or system.
IDEF1x	Data Modeling (Entity-Relation modeling)	IDEF1x is intended as a method for accomplishing the design system activity.
IDEF2	Simulation Modeling	The IDEF2 method development was based on an extensive experience base with continuous, discrete to industrial problems.
IDEF3	Process Description Capture	Two modeling modes exist within IDEF3: process flow description and object state transition description. Process flow descriptions are intended to capture knowledge of "how things work" in an organization. The object state transition description summarized the allowable transitions an object may undergo throughout a particular process.
IDEF4	Object-Oriented Design	IDEF4 is intended to be used as a design method for automated system implementation. IDEF4 targets the use of object-oriented technology, rather than relational technology, for the target implementation.
IDEF5	Ontology Description Capture	IDEF5 is targeted at the construction of reference models that can be used as a basis for both manual and automated identification of similarities, which are appeared in system developments.
IDEF6	Design Rationale Capture	The purpose of IDEF 6 is to facilitate the acquisitions, representation, and manipulation of the design rationale utilized in the development of enterprise level information systems.
IDEF8	User Interface Modeling	
IDEF9	Scenario-Driven IS Design	
IDEF10	Implementation Architecture Modeling	
IDEF11	Information Artifact Modeling	
IDEF12	Organization Modeling	
IDEF13	Three-Schema Mapping Design	
IDEF14	Network Design	

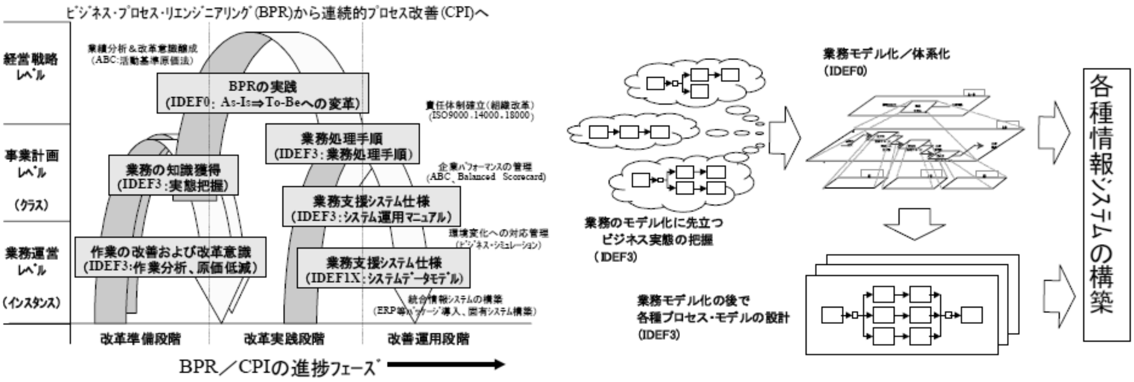


Figure B-1 Occasions of IDEF family in BPR phases (Matsumoto 2003, 2003)

Table B-2 Phases of software system development

Requirement definition	Basic planning	➢ Investigation of user requirements ➢ Analysis of system practicability
	External requirements definitions	➢ Decision of system functions on user requirements ➢ System/data requirements definitions ➢ Definition of GUI and ledger sheet
Design	Internal design	➢ Division of system function into computer programs ➢ Design process sequence
	Program design	➢ Design the internal components and structures of programs ➢ Division of program into modules which are the units of compiling
System build	Programming	➢ Design process flow charts ➢ Coding programs
System proto/ pilot	Implementation test and training	➢ Test of coded programs: unit test, combined test, integrative test, and operational test
Sustainment	Operation, maintenance, and expansion	➢ Fixing bugs ➢ System updating and upgrading

Table B-3 Functional diagrams standardized in UML 2.0 (OMG 2008)

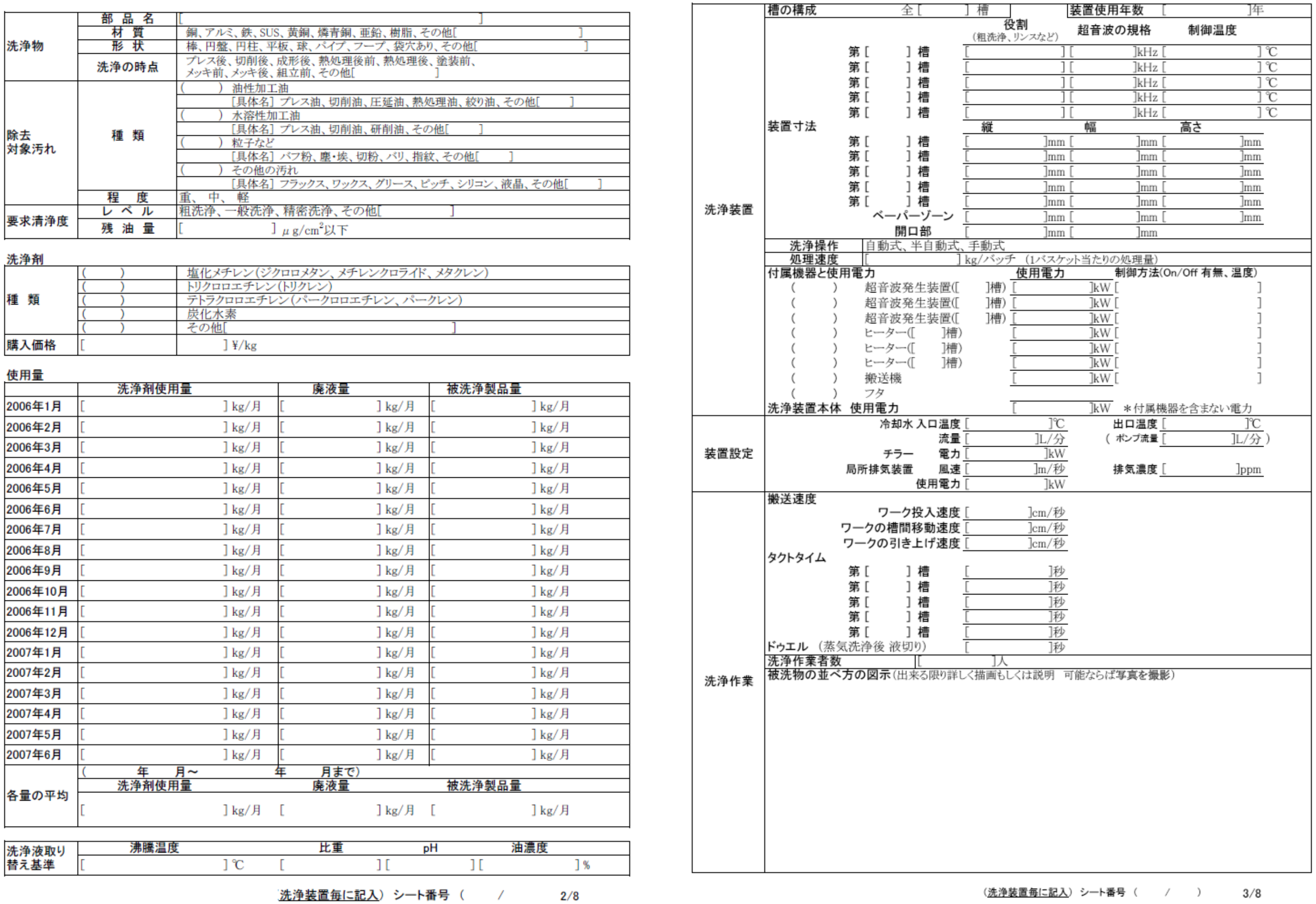
UML diagrams		Content	
Structure	Class	Structure of a system by showing the system's classes, their attributes, and the relationships between the classes	Because of the requirements of knowledge on internal models of system, system developers should construct this model with researchers.
		A complete or partial view of the structure of a modeled system at a specific time	Although the accuracy of model must be evaluated by researchers, system developers should construct this model with class diagram.
	Package	The way how a system is split up into logical groupings by showing the dependencies among these groupings	Package information is belonged to system developers.
		The way how a software system is split up into components and shows the dependencies among these components	Software components must be considered by system developers.
Object	Deployment	Model of the hardware used in system implementations, the components deployed on the hardware, and the associations between those components	The actually installed system components should be considered by all players: decision makers, system developers, and researchers.
Component	Composite structure	Internal structure of a class and the collaborations that this structure makes possible	Software components must be considered by system developers.
Behavior	Use case	Functionality provided by a system in terms of actors, their goals represented as use cases, and any dependencies between those use cases	Researchers must construct this models with the understandings of actual business models of decision makers.
	State machine	Standardized notation to describe many systems, from computer programs to business processes	System developers should construct this model during system development.
	Activity	Business and operational step-by-step workflows of components in a system. An activity diagram shows the overall flow of control	Researchers should construct this model to represent the appropriate information flows among and assigned activities to system and decision makers.
Interaction	Sequence	The way how processes operate with one another and in what order. Also shows about the process change	Researchers should construct a conceptual diagrams to indicate the algorithmic requirements of methods on special knowledge. It should be upgraded to a detail diagrams by system developers.
		Interactions between objects or parts in terms of sequenced messages.	The object of each class should be adequately connected with a specific workflow in software system. System developers should be construct it.
	Interaction overview	A type of activity diagram in which the nodes represent interaction diagrams	System developers should construct this model with a detail sequence diagram.
		A specific type of interaction diagram, where the focus is on timing constraints	System developers should construct this model with a interaction overview.

Communication

Timing

Appendix – C: Investigation on Actual Plant

The investigation is based on the datasheet as shown in **Figure C-1** and **Figure C-2**, which are represented in Japanese. The parts of results are organized in **Table C-1, Table C-2, Table C-3,** and **Table C-4**.



洗浄物	部品名	[ ]
	材質	銅、アルミ、鉄、SUS、黄銅、燐青銅、亜鉛、樹脂、その他[ ]
	形状	棒、円盤、円柱、平板、球、パイプ、フープ、袋穴あり、その他[ ]
	洗浄の時点	プレス後、切削後、成形後、熱処理後前、熱処理後、塗装前、 メッキ前、メッキ後、組立前、その他[ ]
除去 対象汚れ	種類	(　　) 油性加工油
		[具体名] プレス油、切削油、圧延油、熱処理油、絞り油、その他[ ]
		(　　) 水溶性加工油
		[具体名] プレス油、切削油、研削油、その他[ ]
		(　　) 粒子など
		[具体名] バフ粉、塵・埃、切粉、バリ、指紋、その他[ ]
		(　　) その他の汚れ
		[具体名] フラックス、ワックス、グリース、ピッチ、シリコン、液晶、その他[ ]
	程度	重、中、軽
要求清浄度	レベル	粗洗浄、一般洗浄、精密洗浄、その他[ ]
	残油量	[ ] μg/cm²以下

洗浄剤

種類	(　　)	塩化メチレン(ジクロロメタン、メチレンクロライド、メタクレン)
	(　　)	トリクロロエチレン(トリクレン)
	(　　)	テトラクロロエチレン(パークロロエチレン、パークレン)
	(　　)	炭化水素
	(　　)	その他[ ]
購入価格	[	] ¥/kg

使用量

	洗浄剤使用量	廃液量	被洗浄製品量
2006年1月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年2月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年3月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年4月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年5月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年6月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年7月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年8月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年9月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年10月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年11月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2006年12月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年1月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年2月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年3月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年4月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年5月	[ ] kg/月	[ ] kg/月	[ ] kg/月
2007年6月	[ ] kg/月	[ ] kg/月	[ ] kg/月
各量の平均	(　年　月～	年　月まで)	
	洗浄剤使用量	廃液量	被洗浄製品量
	[ ] kg/月	[ ] kg/月	[ ] kg/月

	沸騰温度	比重	pH	油濃度
洗浄液取り替え基準	[ ] ℃	[ ]	[ ]	[ ] %

洗浄装置毎に記入) シート番号 (　/　2/8

洗浄装置

槽の構成　全[ ] 槽　　装置使用年数 [ ]年

	役割 (粗洗浄、リンスなど)	超音波の規格	制御温度
第[ ] 槽	[ ]	[ ]kHz	[ ] ℃
第[ ] 槽	[ ]	[ ]kHz	[ ] ℃
第[ ] 槽	[ ]	[ ]kHz	[ ] ℃
第[ ] 槽	[ ]	[ ]kHz	[ ] ℃
第[ ] 槽	[ ]	[ ]kHz	[ ] ℃

装置寸法

	縦	幅	高さ
第[ ] 槽	[ ]mm	[ ]mm	[ ]mm
第[ ] 槽	[ ]mm	[ ]mm	[ ]mm
第[ ] 槽	[ ]mm	[ ]mm	[ ]mm
第[ ] 槽	[ ]mm	[ ]mm	[ ]mm
第[ ] 槽	[ ]mm	[ ]mm	[ ]mm
ベーパーゾーン	[ ]mm	[ ]mm	[ ]mm
開口部	[ ]mm	[ ]mm	

洗浄操作　自動式、半自動式、手動式

処理速度　[ ] kg/バッチ (1バスケット当たりの処理量)

付属機器と使用電力

		使用電力	制御方法(On/Off 有無、温度)
(　　)	超音波発生装置([ ]槽)	[ ]kW	[ ]
(　　)	超音波発生装置([ ]槽)	[ ]kW	[ ]
(　　)	超音波発生装置([ ]槽)	[ ]kW	[ ]
(　　)	ヒーター([ ]槽)	[ ]kW	[ ]
(　　)	ヒーター([ ]槽)	[ ]kW	[ ]
(　　)	ヒーター([ ]槽)	[ ]kW	[ ]
(　　)	搬送機	[ ]kW	[ ]
(　　)	フタ		

洗浄装置本体　使用電力　[ ]kW　＊付属機器を含まない電力

装置設定

冷却水 入口温度 [ ]℃　　出口温度 [ ]℃
流量 [ ]L/分　　(ポンプ流量 [ ]L/分)
チラー　電力 [ ]kW
局所排気装置　風速 [ ]m/秒　　排気濃度 [ ]ppm
使用電力 [ ]kW

洗浄作業

搬送速度
ワーク投入速度 [ ]cm/秒
ワークの槽間移動速度 [ ]cm/秒
ワークの引き上げ速度 [ ]cm/秒

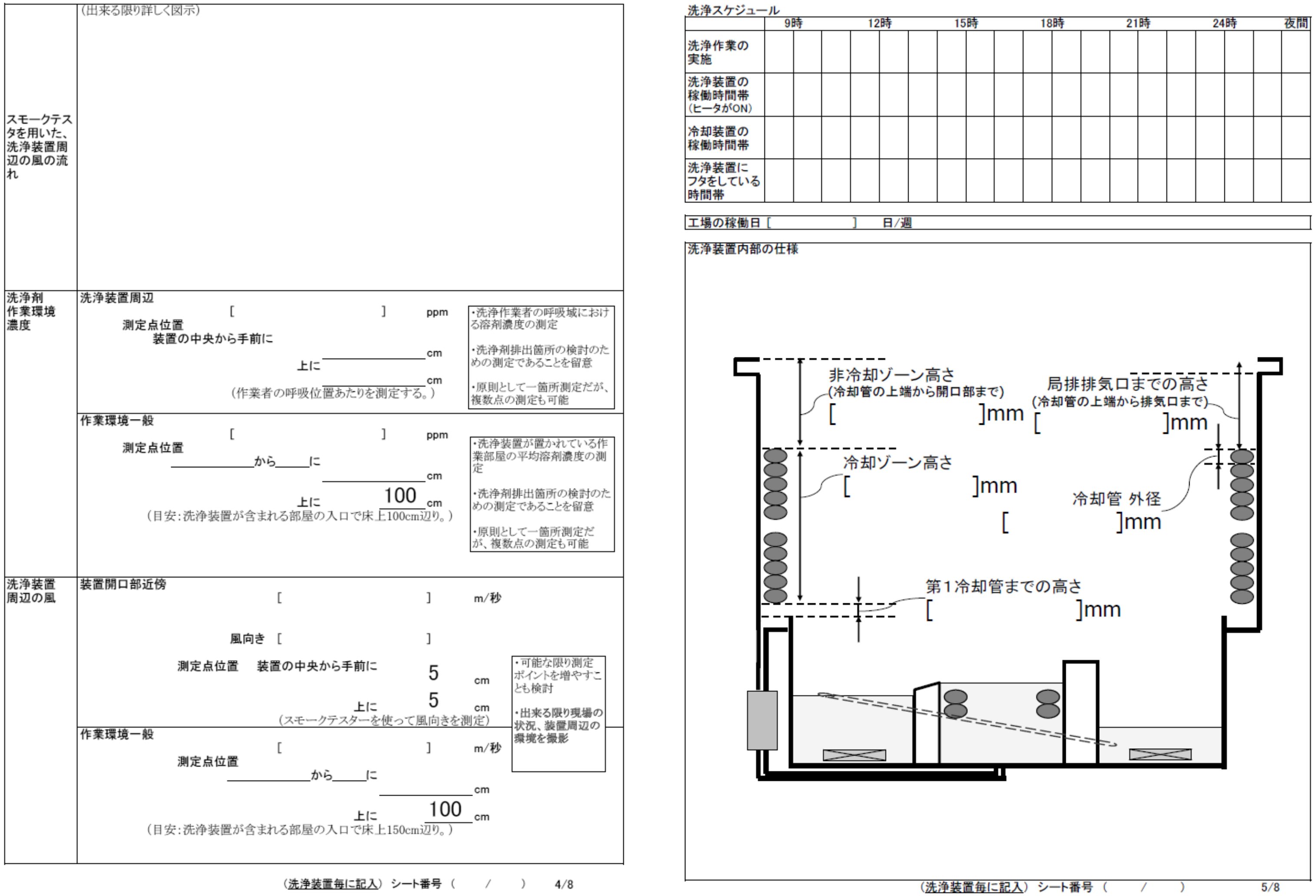
タクトタイム
第[ ] 槽 [ ]秒
第[ ] 槽 [ ]秒
第[ ] 槽 [ ]秒
第[ ] 槽 [ ]秒
第[ ] 槽 [ ]秒
ドゥエル (蒸気洗浄後 液切り) [ ]秒

洗浄作業者数 [ ]人

被洗物の並べ方の図示(出来る限り詳しく描画もしくは説明　可能ならば写真を撮影)

(洗浄装置毎に記入) シート番号 (　/　)　3/8

Figure C-1 Datasheet for the investigation on actual cleaning process



スモークテスタを用いた、洗浄装置周辺の風の流れ	（出来る限り詳しく図示）
洗浄剤作業環境濃度	**洗浄装置周辺** [ ] ppm 測定点位置 装置の中央から手前に ______ cm 上に ______ cm （作業者の呼吸位置あたりを測定する。） ・洗浄作業者の呼吸域における溶剤濃度の測定 ・洗浄剤排出箇所の検討のための測定であることを留意 ・原則として一箇所測定だが、複数点の測定も可能
	作業環境一般 [ ] ppm 測定点位置 ______から______に ______ cm 上に 100 cm （目安：洗浄装置が含まれる部屋の入口で床上100cm辺り。） ・洗浄装置が置かれている作業部屋の平均溶剤濃度の測定 ・洗浄剤排出箇所の検討のための測定であることを留意 ・原則として一箇所測定だが、複数点の測定も可能
洗浄装置周辺の風	**装置開口部近傍** [ ] m/秒 風向き [ ] 測定点位置　装置の中央から手前に 5 cm 上に 5 cm （スモークテスターを使って風向きを測定） ・可能な限り測定ポイントを増やすことも検討 ・出来る限り現場の状況、装置周辺の環境を撮影
	作業環境一般 [ ] m/秒 測定点位置 ______から______に ______ cm 上に 100 cm （目安：洗浄装置が含まれる部屋の入口で床上150cm辺り。）

（洗浄装置毎に記入） シート番号（ / ） 4/8

洗浄スケジュール

		9時			12時			15時			18時			21時			24時		夜間
洗浄作業の実施																			
洗浄装置の稼働時間帯（ヒータがON）																			
冷却装置の稼働時間帯																			
洗浄装置にフタをしている時間帯																			

工場の稼働日 [ ] 日/週

洗浄装置内部の仕様

非冷却ゾーン高さ
(冷却管の上端から開口部まで)
[ ]mm

局排排気口までの高さ
(冷却管の上端から排気口まで)
[ ]mm

冷却ゾーン高さ
[ ]mm

冷却管 外径
[ ]mm

第１冷却管までの高さ
[ ]mm

（洗浄装置毎に記入） シート番号（ / ） 5/8

Figure C-2 Datasheet for the investigation on actual cleaning process

Table C-1 Investigation results 1

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Process phase of cleaning		Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pretreatment (plating)	Pre/posttreatment (heat treatment)	Pre/posttreatment (heat treatment)	Pretreatment (corrosion control)
Cleaning requirement		Precise	Precise	Precise	Precise	Precise	Precise	Precise	Precise	Precise	Normal
Throughput [kg·month^{-1}]		1.97E+04	1.48E+04	1.18E+04	5.88E+03	5.88E+03	6.00E+03	6.00E+03	4.50E+03	1.31E+05	4.88E+05
Cleansing agent		TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE	DCM
Metal parts	Material	1,2,3,4,5,6,7	1,2,3,4,5,6,7	1,2,3,4,5,6,7,8	1,2,3,4,5,6,7,8	1,2,3,4,5,6,7,8	1,3,4,5,9,10	1,3,4,5,9,10	4,5	11	3,7,11
	Shape	D	D	a,b,c,d	a,b,c,d	a,b,c,d	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h,i	a,b,c,d,e,h
Process	Operation	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Hoist	Hoist	Automatic
	Local ventilation	Enclosed-hood	Enclosed-hood	Exterior	Enclosed-exterior	Enclosed-exterior	Exterior	Exterior	Enclosed-exterior	Enclosed-exterior	Enclosed-hood
	Recovery	Null	Null	Installed	Installed	Installed	Null	Null	Null	Null	Null
Input [kg·day^{-1}]	DCM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.73E+02
	TCE	9.24E+01	7.41E+01	6.05E+01	1.67E+01	1.31E+01	2.66E+01	1.52E+01	2.08E+01	9.67E+01	0.00E+00
Utility [MJ·day^{-1}]	Electricity [kWh·day^{-1}]	8.37E+01	6.28E+01	1.52E+02	5.18E+01	4.35E+01	1.25E+02	1.25E+02	1.71E+02	4.83E+02	5.57E+02
	Kerosene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (city gas)	9.36E+02	7.12E+02	1.03E+03	3.94E+02	3.62E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (LPG)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E+04
	Steam (Kerosene)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration [mg·m^{-3}]	Maximum	1.09E+01	1.09E+01	9.83E+01	1.09E+02	5.46E+01	5.32E+01	6.55E+01	4.37E+00	1.37E+01	9.13E+01
	Average	8.74E+00	8.74E+00	4.75E+01	4.75E+01	2.57E+01	2.69E+01	3.04E+01	2.73E+00	8.19E+00	2.82E+01

*1 1: Cu, 2: Al. 3: Fe, 4: SUS, 5: Brass, 6: Bronze, 7: Zn, 8: Plastic, 10: Au, 11: Ag, 12: Steel, 13: Steel with tin-plating

*2 a: Stick, b: Disc, c: Column, d: Plate, e: Ball, f: Pipe, g: Hoop, h: Blind hole, i: Large, j: Concavity and convexity, k: Pod

*3 TCE: Trichloroethylene, DCM: Dichloromethane

Table C-2 Investigation results 2

		Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18	Case 19	Case 20
Process phase of cleaning		Pretreatment (plating)	Pretreatment (corrosion control)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Pretreatment (plating)	Posttreatment (pressing)	Posttreatment (pressing)
Cleaning requirement		Precise	Normal	Normal	Normal	Normal	Normal	Normal	Precise	Normal	Normal
Throughput [kg·month^{-1}]		6.00E+03	1.12E+05	9.91E+04	9.68E+04	9.89E+04	1.15E+05	1.32E+05	8.00E+04	3.00E+04	3.00E+04
Cleansing agent		TCE	DCM	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE
Metal parts	Material	3,7,11	1	1	1	1	1	1	2,3,4	12	3,11
	Shape	A,b,c,d,e,h	f,i	f,i	f,i	f,i	f,i	f,i	a,b,c,d,e,h,i	c,k	a,c,h,j
Process	Operation	Hoist	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Hoist	Automatic	Hoist
	Local ventilation	Enclosed-exterior	Enclosed-hood	Enclosed-hood	Enclosed-hood	Enclosed-hood	Enclosed-hood	Enclosed-hood	Exterior	Exterior	Exterior
	Recovery	Null	Null	Null	Installed	Installed	Installed	Installed	Null	Null	Null
Input [kg·day^{-1}]	DCM	3.96E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.13E+01
	TCE	0.00E+00	5.43E+02	4.80E+02	3.12E+02	2.83E+02	1.64E+02	1.51E+02	7.31E+01	3.19E+01	0.00E+00
Utility [MJ·day^{-1}]	Electricity [kWh·day^{-1}]	1.33E+02	1.61E+03	1.73E+03	1.73E+03	1.73E+03	4.38E+02	4.38E+02	1.73E+02	5.89E+02	2.30E+02
	Kerosene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (city gas)	0.00E+00	0.00E+00	4.74E+02	4.74E+02	4.74E+02	1.70E+04	1.70E+04	3.50E+02	0.00E+00	0.00E+00
	Steam (LPG)	1.51E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (Kerosene)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration [mg·m^{-3}]	Maximum	1.16E+02	3.93E+02	4.24E+02	1.12E+02	3.32E+02	2.49E+02	3.78E+02	1.39E+02	1.69E+02	1.91E+02
	Average	2.82E+01	9.83E+01	1.09E+02	4.53E+01	1.11E+02	6.93E+01	9.01E+01	7.15E+01	4.68E+01	1.20E+02

*1 1: Cu, 2: Al. 3: Fe, 4: SUS, 5: Brass, 6: Bronze, 7: Zn, 8: Plastic, 10: Au, 11: Ag, 12: Steel, 13: Steel with tin-plating

*2 a: Stick, b: Disc, c: Column, d: Plate, e: Ball, f: Pipe, g: Hoop, h: Blind hole, i: Large, j: Concavity and convexity, k: Pod

*3 TCE: Trichloroethylene, DCM: Dichloromethane

Table C-3 Investigation results 3

		Case 21	Case 22	Case 23	Case 24	Case 25	Case 26	Case 27	Case 28	Case 29	Case 30
Process phase of cleaning		Pretreatment (corrosion control)	Pretreatment (coating)	Pretreatment (coating)	Posttreatment (cutting)	Posttreatment (cutting)	Pre/posttreatment (heat treatment)	Pre/posttreatment (heat treatment)	Pre/posttreatment (heat treatment)	Pretreatment (plating)	Pretreatment (plating)
Cleaning requirement		Normal	Precise	Precise	Precise	Normal	Precise	Precise	Precise	Precise	Precise
Throughput [kg·month^{-1}]		1.12E+05	6.60E+03	8.16E+03	9.99E+03	1.16E+04	9.90E+03	1.73E+05	2.27E+04	5.76E+03	5.76E+03
Cleansing agent		DCM	DCM	TCE	TCE	TCE	TCE	TCE	TCE	TCE	TCE
Metal parts	Material	3,11	3,11	4	4	3,7,11	3,7,11	3,7,11	3,7,11	1,2,3,4,5	1,2,3,4,5
	Shape	a,c,h,j	a,c,h,j	b,k	b,k	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,e,h	a,b,c,d,f,h	a,b,c,d,f,h
Process	Operation	Automatic	Hoist	Automatic	Automatic	Hoist	Automatic	Automatic	Hoist	Manual	Manual
	Local ventilation	Exterior	Exterior	Enclosed-hood	Enclosed-hood	Exterior	Enclosed-hood	Enclosed-hood	Exterior	Exterior	Exterior
	Recovery	Null	Null	Installed	Installed	Null	Null	Null	Null	Null	Null
Input [kg·day^{-1}]	DCM	1.13E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	TCE	0.00E+00	1.01E+01	2.70E+01	2.64E+01	7.23E+01	2.41E+01	1.76E+02	4.82E+01	2.55E+01	1.03E+01
Utility [MJ·day^{-1}]	Electricity [kWh·day^{-1}]	4.61E+02	2.84E+01	4.48E+01	4.48E+01	9.75E+01	4.40E+01	6.36E+02	2.10E+02	3.20E+01	3.20E+01
	Kerosene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (city gas)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (LPG)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Steam (Kerosene)	0.00E+00	0.00E+00	7.10E+02	1.03E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration [mg·m^{-3}]	Maximum	4.86E+01	7.10E+00	4.37E+01	4.23E+01	1.43E+02	1.43E+02	1.52E+02	1.52E+02	1.47E+02	2.16E+02
	Average	4.51E+00	5.46E+00	3.70E+01	3.79E+01	4.10E+01	4.10E+01	5.30E+01	5.30E+01	1.20E+02	1.62E+02

*1 1: Cu, 2: Al. 3: Fe, 4: SUS, 5: Brass, 6: Bronze, 7: Zn, 8: Plastic, 10: Au, 11: Ag, 12: Steel, 13: Steel with tin-plating

*2 a: Stick, b: Disc, c: Column, d: Plate, e: Ball, f: Pipe, g: Hoop, h: Blind hole, i: Large, j: Concavity and convexity, k: Pod

*3 TCE: Trichloroethylene, DCM: Dichloromethane

Table C-4 Investigation results 4

		Case 31	Case 32	Case 33	Case 34	Case 35	Case 36	Case 37
Process phase of cleaning		Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)	Posttreatment (cutting)
Cleaning requirement		Normal	Normal	Normal	Normal	Normal	Normal	Normal
Throughput [kg·month^{-1}]		3.30E+04	1.17E+05	1.17E+05	1.17E+05	1.17E+05	1.17E+05	1.17E+05
Cleansing agent		TCE	HC	DCM	DCM	DCM	DCM	DCM
Metal parts	Material	4	2,3,4,	1, 4, 7	1, 4, 7	1, 4, 7	1, 4, 7	1, 4, 7
	Shape	b,k	d	h, j	h, j	h, j	h, j	h, j
Process	Operation	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic
	Local ventilation	Enclosed-hood	Enclosed-hood	Exterior	Exterior	Exterior	Enclosed-exterior	Exterior
	Recovery	Installed	Installed	Null	Null	Null	Null	Install
Input [kg·day^{-1}]	DCM	0.00E+00	0.00E+00	1.18E+02	2.80E+01	1.64E+02	3.22E+01	1.18E+02
	TCE	2.01E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	HC	0.00E+00	1.69E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Utility [MJ·day^{-1}]	Electricity [kWh·day^{-1}]	7.55E+01	1.15E+01	6.16E+01	5.44E+01	6.64E+01	6.40E+01	7.52E+01
	Kerosene	1.86E+03	4.51E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Workplace concentration [mg·m^{-3}]	Maximum	4.73E+01	-	2.29E+01	5.73E+01	1.37E+01	4.57E+00	2.29E+01
	Average	3.26E+01	-	-	-	-	-	-

*1 1: Cu, 2: Al. 3: Fe, 4: SUS, 5: Brass, 6: Bronze, 7: Zn, 8: Plastic, 10: Au, 11: Ag, 12: Steel, 13: Steel with tin-plating

*2 a: Stick, b: Disc, c: Column, d: Plate, e: Ball, f: Pipe, g: Hoop, h: Blind hole, i: Large, j: Concavity and convexity, k: Pod

*3 TCE: Trichloroethylene, DCM: Dichloromethane, HC: Hydro carbon

Appendix – D: Substance Physical Property

Table D-1 Physical and Hazardous Properties of Substances Utilized as Cleansing Agents

Substance		Dichloromethane	Trichloroethylene
Physical property			
Molecular weight		84.9	131.39
CAS number		75-09-2	79-01-6
Boiling point	°C	40.2	86.9
Melting point	°C	-95.1	-84.8
Relative density (water = 1)		1.3	1.4559
Solubility in water, at 20°C	g/100ml	1.3	0.128
Vapour pressure, kPa at 20°C	kPa	47.4	7.8
Relative vapour density (air = 1)		2.93	4.54
Relative density of the vapour/air-mixture at 20°C (air = 1)		1.9	1.3
Auto-ignition temperature	°C	556	410
Explosive limits, vol% in air	vol %	12-25	8-10.5
Octanol/water partition coefficient as log Pow		1.25	2.42
Occupational exposure limit			
JSOH	ppm	50 (2006)	25 (2006)
ACGIH-TLV (TWA)	ppm	50 (2002)	10 (2007)
ACGIH-TLV (TSTEL 15min)	ppm	N/A	25 (2007)
OSHA-PEL (TWA)	ppm	25 (1998)	100 (1998)
OSHA-PEL (STEL)	ppm	125 (1998)	N/A
DFG-MAK	ppm	100	(Insufficient data available for establish MAK value)

Table D-2 Physical and Hazardous Properties of Substances Utilized as Cleansing Agents

Substance			Dichloromethane	Trichloroethylene
Non-carcinogenic effect				
NOAEL		ppm	35.7 (Nakanishi and Inoue 2005)	13 (Kajiwara and Kawasaki 2008)
	(UFs)			100
	(RfD)	ppm	0.357	0.13
Carcinogen category				
JSOH			2B (2006) Possibly carcinogen	2B (2006) Possibly carcinogen
IARC			2B (1999) Possibly carcinogen	2A (1999) Probably carcinogen
US EPA			B2 (1999) Possibly carcinogen with sufficient evidence from animal studies and for which there is "inadequate evidence" or "no data" from epidemiologic studies	N/A
ACGIH		100	A3 (2002) Confirmed animal carcinogen with unknown relevance to humans	A5 (2002) Not suspected as a human carcinogen
DFG			3A Chemicals which are suspected of being germ cell mutagens	1 Germ cell mutagens which have been shown to increase the mutant frequency in the progeny of exposed mammals