博士論文

Systemic Intensification of Agriculture and Industry in Plant-Derived Production
（植物資源由来生産における農業と工業のシステミックな強化）

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Systemic Intensification of Agriculture and Industry in Plant-Derived Production

(植物資源由来生産における農業と工業のシステミックな強化)

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Abstract

While utilizing plant-derived resources has emerged as a key toward sustainability, systems should solve systemic problems that cannot be easily coped with because of their far-reaching and potentially unpredicted influence. For example, in combined sugar and ethanol production from sugarcane, the cultivar choice by farmers in agricultural stages will influence the characteristics of sugarcane such as yield and compositions. These characteristics may affect the performance and the operations in industrial stages especially if the feedstocks comprising much impurities are chosen. On the other hand, if the engineers in the sugar mill prepare in advance treatment units such as introduction of a technology that can mitigate the unpleasant effects from the impurities, farmers can choose cultivars from wider range of choices, but it may be hard for them to make such decision without building consensus with farmers.

Although systems design considering agricultural and industrial options simultaneously may untangle such systemic problems and offer some opportunities for intensifying plant-derived production that cannot be found until the present, it is challenging to practice because there are some obstacles to be discussed quantitatively; different time scales, data availability, uncertainties as well as decision makers between agriculture and industry. A modeling approach that has played an important role in assisting design of such complex systems design should help decision makers understand their interactions and contribute to overcome such obstacles.

In this study, “systemic intensification” was proposed as a new concept of systems design to tackle with the systemic problems in plant-derived production. As mechanisms required for systemic intensification, a model that can analyze agriculture and industry in an integrated manner and a method for planning transition to the intensified system were developed through a case study on sugarcane-derived production. Based on the products from these case studies, a framework of planning scenario for intensifying agriculture and industry in plant-derived production was developed. The applicability of the framework was examined based on two case studies: rice-bran oil refinery and plant factory. Finally, with the framework developed in this study, the decision makers in plant-derived production would prepare mechanisms through proactively involving mechanism developers, produce a practical scenario plans, develop technology for achieving the plan and encourage the awareness of stakeholders.

Contents

Chapter 1. Introduction

1.1. Utilization of Plant-Derived Resources

There is an increasing awareness of the importance of resources that can replace fossil resources such as oil, gas and coal to meet the growing global demands of energy and chemicals as population and prosperity levels increase worldwide (Smil, 2005). Fossil fuels are widely used in transport, agriculture, commercial, domestic and industrial sectors for the generation of power or mechanical energy worldwide (Demirbas, 2009). In transport sectors, around 98% of the total energy consumed is derived from fossil fuel. Regarding chemical industries, the majority of chemical products are produced from oil refinery, consuming almost 4% of oil in the world (Nossin, 2009). Although fossil resources seem to be able to meet our demand for more than 50 years due to the discovery and exploitation of new oil and gas reserves, they are eventually destined to be depleted (Smil, 2005). Since the places where those resources are accessible are limited, the conflicts of interest on them could be evolved into political issues. In addition, the consumption of fossil resources has caused a number of environmental issues. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report highlighted the clear evidence that the climate change in the earth has been caused by the emissions of greenhouse gases from fossil fuel combustion and land-use change as a result of human activities (IPCC, 2007). Therefore, it is important to identify and establish the way of utilizing alternative resources to avoid the above concerns.

Biomass resources, which are all biologically-produced matter based in carbon, hydrogen and oxygen, are the key alternatives to fossil resources for production of both fuels and chemicals. They are the only carbon-rich material source available on the earth besides fossils. In general, biomass resources can be renewable and accessible in places where it is difficult to obtain fossil resources. Their use also avoids the fluctuations of international gas and petroleum prices, offering opportunities for secure provision of heat, liquid fuels, and chemicals. Moreover, producing fuels and chemicals derived from biomass can decrease the environmental impacts in some cases (e.g., Jaccard, 2005).

Among biomass resources, plant-derived resources such as agricultural energy crops and residues and forestry wastes have been received attention and their conversion technology has been intensively studied. Currently, biofuels are classified into first and second-generation ones. First-generation biofuels are produced from sugar, starch, or vegetable oil. Because their resources are in competition with food and feed industries, these biofuels give rise to ethical, political and environmental concerns. Second-generation biofuels, which are produced from non-food crop or inedible part of crops, emerged as the next candidates to overcome the issues of first-generation ones. As a development of the production of first and second generation biofuels, a biorefinery concept, where multiple products such as bioenergy and chemicals are coproduced from plants, has been emerged to ensure additional economic and environmental benefits (Cherubini, 2010). This concept has accelerated the commercialization of both first and second-generation biofuels.

In addition to research and development activities, the governments in many countries have supported the utilization of biomass resources. For example, the Japanese government decided upon “Biomass Nippon Strategy” at the cabinet meeting to promote the biomass utilization in December 2002. This was the first national strategy for Japan to utilize biomass as valuable resource, and a comprehensive one including the viewpoints of technology, social system and economy (Kuzuhara, 2005). Thanks to the researches and the political supports, existing plant-derived resources have been partially utilized. Figure 1-1 shows the estimated abundance of biomass resources in 2016 in Japan. More than half the biomass generated is utilized for some purposes regarding animal wastes, sewage sludge, black liquor, paper, sawmill remaining, and timber from construction. However, 68% of inedible parts of agricultural crops, 76% of food wastes, and 91% of forest residues still remain untouched. According to MIC, Japan (2011), 179 out of 214 of national projects related to biomass were accounted ineffective and most of them are not economically competitive with fossil-utilized business. Practical utilization of biomass including plant-derived resources is still in a developing stage.

1.2. Problems of Agriculture and Industry in Plant-Derived Production

Many engineers have tackled with the development of technology for utilizing plant-derived resources as they have done for fossil resources. The purpose of research has been set by subdividing the problems into small ones to facilitate making full use of their own expertise. For example, the optimal conditions for controlling the microorganisms have been studied to reduce the cost of the biomass conversion in the field of biotechnology.

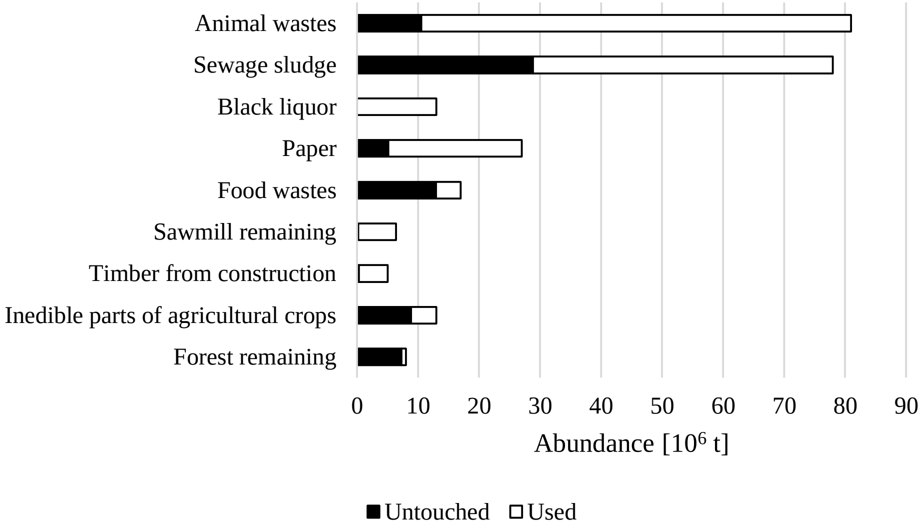


Figure 1-1 Estimated abundance of biomass resources in Japan (Calculated based on MAFF, Japan, 2016)

Engineers tend to engage in the discussion within their engineering fields. With regard to plant-derived production, they have made their efforts on the application of engineering technology obtained from oil refinery to biorefinery. The raw material has been considered to be readily available as they need. However, the premise of the problems that they have established is sometimes inappropriate or not enough to solve the actual problems. The difference in characteristics between fossil-derived and plant-derived productions has been occasionally overlooked. Figure 1-2 illustrates the difference between them. The stage of raw material acquisition for the fossil-derived production is mining, whereas that for plant-derived production is forestry or agriculture. While forestry-derived products require appropriate management over generations, agricultural products are manageable because farming is in units of years. Because agricultural crops are cultivated outside in general, a yield and composition of crops are exposure to the risk from weather conditions such as storms and droughts. Seasonality of plant growth and its maturity temporarily limit the provision of crops, while one can procure as much fossil resources as they want from mining companies through all seasons. As involvement of farmers is indispensable to provide agricultural crops and residues, a decrease in the population of farmers may give serious impacts on their conversion stages. With regard to agricultural residues, it should be noted that crops are cultivated for other main purposes such as food production. Farm operations for the main purposes may not be suitable to the residues production. In spite of the above differences between fossil-derived and plant-derived productions, engineers may not pay enough attention to them.

It is also difficult for farmers and agricultural researchers to imagine how the crops are processed and utilized in their downstream processes. In general, they regard agricultural crops as final products and do not have the engineering knowledge related to the conversion after shipping. Their knowledge and efforts are devoted to the main product alone.

Agriculture has not necessarily been designed considering industry and vice versa. There is sometimes mismatching between problems to solve and the technology developed for the problems in plant-derived production because of the limited viewpoints of both agricultural and industrial sides as described above. Although the agriculture and industry are closely related, their cause and effect relationships across them are sometimes overlooked and only problems that are easily recognizable are prone to draw attention. Eventually, the implemented solution may not fulfill its potential. On the contrary, a decision making with little understanding of their relationship sometimes causes a great disaster. For example, the specified production standard of biofuels has been set by the government in America since 2007 to promote the production from renewable resources such as corn-derived bioethanol production. However, this policy causes the skyrocketing of corn prices. One of the reason could be lack of understanding the complex behavior of the systems of agriculture and industry. A systems design methodology dealing with the whole range through agriculture and industry is necessitated.

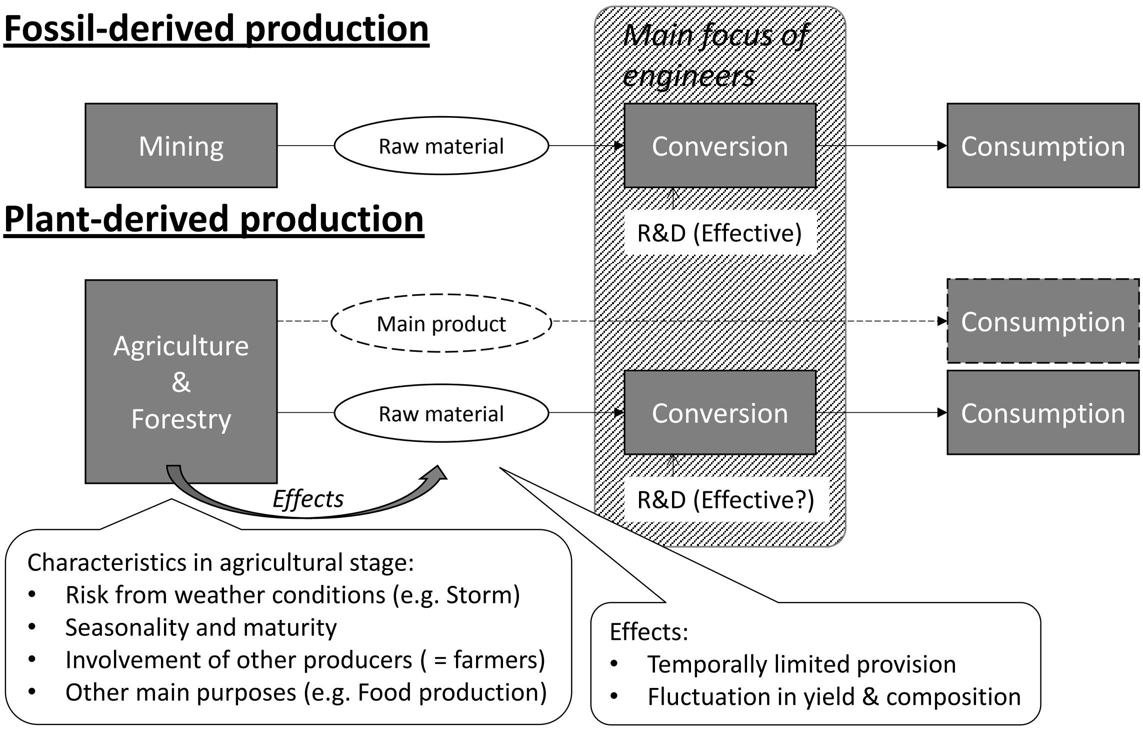


Figure 1-2 Difference in characteristics between fossil-derived production and plant-derived one.

1.3. Solution for Problems Derived from Mismatching between Problems and Solutions

Plant-derived production can be regarded as a complex system where multi-decision makers exist and one cannot necessarily solve problems because it is difficult to imagine the effects of his or her decision on others and the whole system. Process systems engineering (PSE) and computer-aided process engineering (CAPE) have played important roles in understanding and designing a system, enabling to avoid problems derived from the mismatching between problems to solve and solutions.

Traditionally, the progress of PSE and CAPE fields has achieved through its efforts on chemical process designs (Naraharisetti et al., 2009). They have successfully developed a systematic method of designing chemical processes (Biegler, 1997; Duncan and Reimer, 1998) based on modeling, simulation and optimization. A systematic framework has been developed by integrating evaluation methods and these existing tools in order to support multi-objective decision-making required for environmentally conscious process design (Chen and Shonnard, 2004). In addition, the framework of process design incorporating life cycle assessment (LCA) and risk assessment (RA) into these tools has been also developed (Kikuchi and Hirao, 2009).

In the past decades, PSE has expanded to support systems design involving multi-decision makers by leveraging its fundamental expertise in synthesizing data. Decision support for chemical supply chains has emerged as a major area of research in PSE (Grossmann, 2005; Naraharisetti et al. 2008). Optimal design of biomass supply chain networks has analyzed based on simulation (e.g. Kim et al., 2011; Dunnett et al., 2008; Kumar and Sokhansanj, 2007) A practical framework of chemical risk management based on process design considering collaboration task among supply chains has been developed (Kikuchi-Uehara et al., 2014). Kanematsu et al. (2017a) developed a framework of industrial symbiosis in rural areas. The methodology of multiple criteria decision making based on modeling has been developed (Kahraman, 2008) and applied to engineering problems such as energy systems for sustainability (Wang et al., 2009).

Although PSE has dealt with various kinds of design problems, it has not been applied to the design of systems that include agriculture. PSE offers a powerful set of methods and tools for systems problems solving in all those domains which share a lot in common with chemical engineering even if they are not considered to be part of this field (Klatt and Marquardt, 2009). However, it should be noted that the transfer of methods and tools to a new domain may reveal new requirements which have not been faced yet. The systems of agriculture and industry in plant-derived production has distinctive features in terms of the gap of spatial and temporal scales and uncertainties within the systems. PSE should tackle with this new challenge to extend the domain of its application.

1.4. Intensifying Systems through Solving Systemic Problems

Agriculture and industry have been designed individually: options in only one side have been available considering options in another as given ones. Integrated design of agriculture and industry may have a potential of generating new alternatives that have not been found in the previous way. Since it has been difficult to deal with problems related to both agriculture and industry in plant-derived production, they may arise as vulnerability issues of the whole systems. Development of the method of the integrated design should give us another view for the unsolved problems or another beneficial solution for all players without conflicts of interest, namely intensifying the systems.

Agriculture and industry are different in spatial and temporal scales. In general, plant-derived resources are processed in factories continuously, whereas they are produced on farmlands that have far larger area than factories have in seasons or years. Multiple spatial and temporal scales design has been recent challenges for advanced systems design (Klatt and Marquardt, 2009). Traversing the scales could change the number and type of degrees of freedom and generate innovative alternatives. Such approach would be a key to the design of systems related to human activities considering water-energy-food nexus for sustainability (Garcia and You, 2016). Because it is so expensive to deal with multiple spatial and temporal scales that detailed process systems model do not yet exist at a level satisfactory for actual decision makings.

Process intensification (PI) has been an emerging strategy for the design of competent and sustainable chemical processes through traversing different design scales. Without clear agreement yet on what the term means, Stankiewicz and Moulijn (2000) have temporarily given the general definition as follows:

Process intensification consists of the development of novel apparatuses and techniques that, compared to those commonly used today, are expected to bring dramatic improvements in manufacturing and processing, substantially decreasing equipment-size/production-capacity ratio, energy consumption, or waste production, and ultimately resulting in cheaper, sustainable technologies.

According to this statement, PI via engineering methods supports the significant improvement of process performance in productivity, safety and environmentally-friendliness in addition to reductions in plant size. The reactive distillation process, where a reactor and a distillation column are integrated in one process unit, is one of the examples of PI. The examples of significant process simplification can be found in the previous research papers (e.g., Zwijnenburg et al., 1998).

The objective of process intensification is to generate innovative flowsheet alternatives that incorporate hybrid/intensified unit operations, subject to predefined process constraints, design targets and performance criteria (Siirola, 1996; Ozkan et al., 2012; Lutze et al., 2013; Babi et al., 2015). Process intensification is performed at three different scales (plant/unit operation, functional/task and phenomena/molecular) and four domains (spatial, thermodynamic, functional and temporal) if abstractly represented (Van Gerven and Stankiewicz, 2009). Simultaneous design of parameters in different scales generates more innovative flowsheet alternatives compared to the previous way because the search space of unit operations available for the generation widens (Lutze et al., 2013; Babi et al., 2015). One effective way to generate such an innovative alternative can be modeling approach from a multiscale viewpoint that involves material, device and process design (Kuroda et al. 2008). Mathematical programming, heuristics, and their hybrid have contributed to the generation of PI-based alternatives. Some CAPE-based frameworks have proposed to achieve PI systematically (e.g., Babi et al., 2015).

When we develop the methodology for intensifying the systems of agriculture and industry in plant-derived production, additional requirements derived from its characteristics should be taken into account as mentioned in Chapter 1.3. There are four major distinctive features in agriculture compared with industry (Nanseki and Fujii, 2015). One is the indirectness. Unlike industrial products, agricultural crops are not synthesized by operators' direct actions. Instead, they are brought up through the control of the environment, which indirectly fosters the growth. The second is the openness to the environment. The yield and composition of agricultural crops are greatly influenced by uncontrollable environmental factors. The third is the number of business players. In general, there are quite a few farmers, depending on the case. This situation will lead the ununiformity of agricultural crops. The forth is the low reproducibility of the experimental results. Since it takes months or a year to cultivate crops, countless number of factors are involved in the final outcome.

Because these features bring about large uncertainties in agriculture, there remains a lot of unclear relationship among the factors in agriculture. In fact, empirical knowledge has played an important role in this field. Consequently, the cause and effect relationship across agriculture and industry has become vague. It is difficult for actual decision makers to clearly identify which factors cause the problem because of the combination of the above features. Nevertheless, one's decision making sometimes unconsciously causes others' problems or is potentially the key to their solutions.

A problem caused by multiple factors including the hardly-identifiable one is called a systemic problem in this thesis. As described above, there seems systemic problems that are obstacles to intensification of the systems of agriculture and industry in plant-derived production. It may be true that just modeling approach that has been applied in industrial fields is not enough to support the decision makings. However, there has been no way to design systems of agriculture and industry based on quantitative discussion although problems are emerging one another and data and knowledge exist in subdivided fields. PSE should tackle with this challenge making full use of its fundamental expertise in modeling, simulation and supporting decision-makings.

1.5. Objectives and Thesis Structure

This study is aimed at the development of the method for intensifying the systems of agriculture and industry in plant-derived production. As an approach for achieving the goal, systemic intensification is proposed in this thesis.

The structure of this PhD thesis is shown in Figure 1-3. The concept of systemic intensification and its requirements are proposed based on the actual problems in plant-derived production in Chapter 2. Actual problems in plant-derived production and their rationales are identified. Based on the findings, the concept of systemic intensification and its required mechanisms is proposed. Method for analysis integrating agricultural and industrial processes are developed in Chapter 3, taking sugarcane-derived production as a case study. Chapter 4 focuses on a scenario planning method. A scenario planning meeting was conducted to verify its function as a mechanism to support practicable scenario generation considering agricultural and industrial options. On the basis of findings in Chapter 2-4, the framework for systemic intensification is embodied using activity modeling method, IDEF0. The usage of developed mechanisms and procedure of proposal for systemic intensification are represented in the model. In Chapter 6, the framework developed in Chapter 5 is applied to the cases other than sugarcane-derived production in order to verify its general applicability.

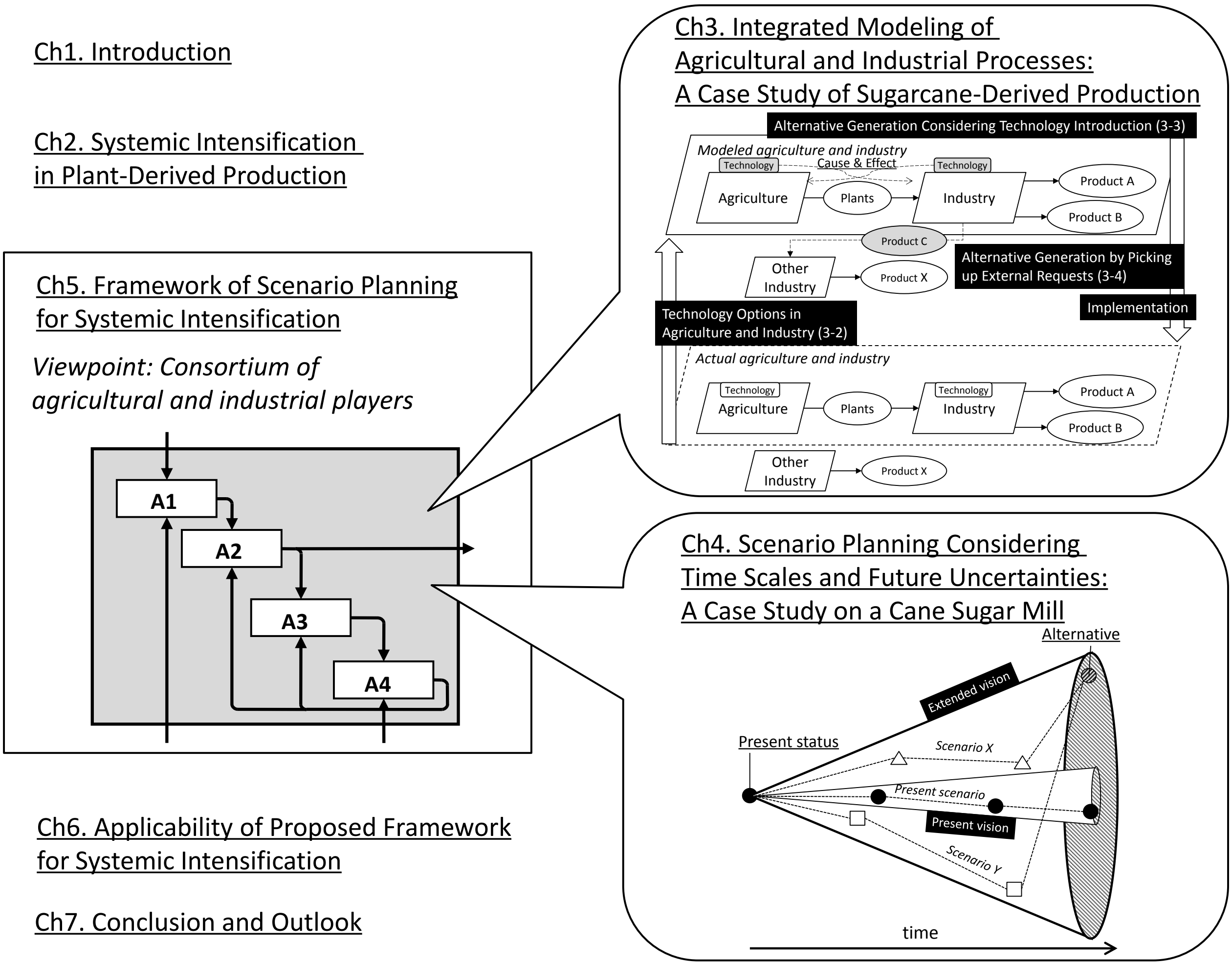


Figure 1-3 Structure of this PhD thesis.

Chapter 2. Systemic Intensification in Plant-Derived Production

Solving systemic problems in plant-derived production sometimes requires decision makers to change their paradigm from the conventional way of thinking that focuses on a problem in a narrow scope. They have to be conscious of the effects of their decision on the others' interests and even the interests of themselves involving macro system including them. As discussed in Chapter 1, the systems design approach has been an activity to create alternatives for the current system to search for more desirable systems by screening them under various constraints. However, it is challenging for actual decision makers to consider beyond their current scope, especially of farmers for industrial processes and of engineers in industry for agricultural processes. Some mechanisms for assisting the systems design through solving systemic problems in systems of agriculture and industry are required. The purpose of Chapter 2 is to propose a new concept called "systemic intensification" and mechanisms to be developed for achieving it.

2.1. Problems Rationalization

2.1.1. Problem Identification in Agriculture and Industry

Problems and approaches to solving them in plant-derived production have changed and varied with the times. Traditionally, problems that arise in agriculture and industry are dealt with in agricultural and engineering fields, respectively. In the ancient times, agriculture began to provide foods and materials required for human activities satisfactorily. Agricultural crop production has increased and stabilized through the extensification and intensification of arable land. Because it has been gradually difficult to expect the further extensification considering the limited remaining land resources, the knowledge and technology for intensifying existing farmland has attracted growing attention. Good cultivar breeding and methods of raising seedlings and cultivation management such as irrigation, fertilization, prevention and extermination have been studied to increase and stabilize the production in the agricultural field.

Agricultural crops consume months or years to get mature and are greatly influenced by environmental conditions, resulting in high uncertainties in their yield and compositions. Therefore, it is hard to get the experimental results that has reproducibility sufficient for identifying the relationship among the specific parameters. Empirical knowledge has practically utilized in actual farming. The concept that has emerged recently and represented this characteristic is sustainable crop intensification (SRI-Rice, 2013). Although the terminology used can vary: sustainable intensification of agricultural production (Royal Society, 2009; Montpellier Panel, 2013), sustainable agricultural intensification (IFAD/UNEP, 2013; World Bank, 2006), sustainable crop production intensification (FAO, 2011), and low-input intensification (European Parliament 2009), the intended redirection of thinking and practice is broadly shared. This approach does not only intends to yield more output from a given amount of inputs, but also aims to achieve higher output with less use of or less expenditure on land, labor, capital, and water by modifying crop management practices (SRI-Rice, 2013). Empirical knowledge is a key to success of such an approach, although its methodology is still on a developing stage.

The engineering field has strongly supported the intensification of agriculture. Material and mechanical resources developed in engineering field have been applied to crop production. For example, Haber–Bosch process, which has been developed in 1906 to synthesize ammonia from nitrogen in the air on an industrial scale, has greatly enhanced the productivity of cultivation. Similarly, engineering has succeed in synthesizing agrochemicals from petroleum, reducing the risk from diseases, insects and weeds. Agricultural machineries such as tractors and harvesters have helped famers to manage cultivation with small labor. As a recent engineering technology, sensing technology has been applied to convert empirical knowledge into explicit knowledge through collecting data and analysis and support farmers' decision. Robotics have been expected to reduce labor costs through automated farming. Plant factories, which produce agricultural crops inside the building under the controlled environmental conditions, are also promising technological options to enhance the food security.

Engineering technology has been applied to not only production of agricultural crops but also their conversion. For example, industrial crops such as rapeseed for edible oil, potatoes for alcohol and beet for sugar are converted into final crops via engineering technologies. Recently, there have been researches on the conversion of biomass such as byproducts and residues into fuels or other value-added products. Because such crops and biomass are processed in factories, the related technologies are mainly developed in the engineering field.

The approaches introduced above have targeted the problem in the range that a single decision maker can deal with. However, recent agricultural problems have been strongly related to sustainability issues and recognized to be tackled with based on multidisciplinary research (Lockeretz, 1991). For example in Japan, the concept of sixth sector, which is the integration of food supply chain and value chain where farm producers and consumers are connected, has been promoted for regional invigoration (Saito, 2012). Information and Communication Technology (ICT) is crucial to form the solid networking among them. Although there are still many problems such as the diffusion of ICT devices among farmers and the insufficiency of data, it should offer other solutions through the management of the supply and value chains.

Many engineering research shown above have been based on reductionism, that is, the way of thinking that the world is a set of systems and that these can be systematically engineered to achieve objectives (Checkland, 2000). However, there is a limit to solving problems as long as we only rely on reductionism. In the next section, actual problems that are hardly solved based on reductionism are explained.

2.1.2. Problem Examples in Plant-Derived Production

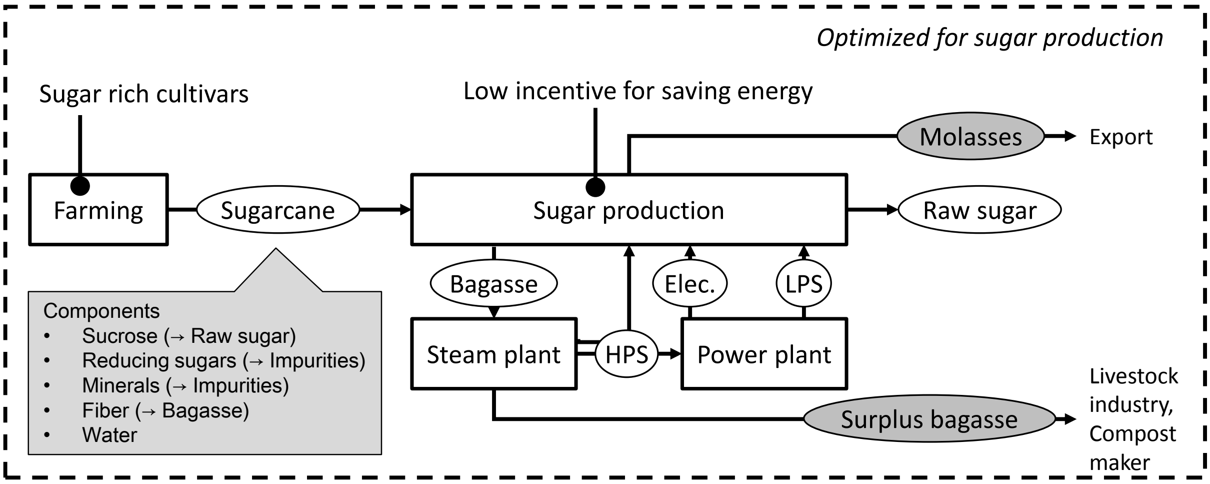
Actual problems in plant-derived production are examined for three cases: sugarcane-derived production, rice-derived production and production from plant factories.

A) Sugarcane-derived production

Sugarcane is one of the key crops to meet growing demands of raw sugar, bioethanol and electricity. Approximately 80% of the world sugar production has been from sugarcane. It is projected that it will account for virtually all of the additional sugar production and represent nearly 86% of sugar production in 2023 (OECD and FAO, 2014). At the same time, the production of bioethanol from the saccharides of sugarcane has been one of the world’s most commercially successful biofuel production systems (Hoang et al., 2015). Its environmental benefits such as reducing greenhouse gas emissions and fossil resource consumption have been also reported (Kikuchi et al., 2013; Nguyen et al., 2011). Some cane sugar mills have produced not only sugar and bioethanol but also electricity and composts. The technologies for producing them or other new products efficiently have been studied (Gheewala et al., 2011; Gnansounou et al., 2015; Pereira et al., 2015).

Unlike the growing importance of sugarcane, a further increase in farmland area is not expected, considering the limited remaining land resources. The strategy for an increase in productivity per arable land is required to meet the world demands. Nevertheless, there remains a considerable amount of sugarcane only used for sugar production.

For example, in the south-western islands in Japan, a raw sugar alone has been regarded as the final product in all sugar mill companies as ever. Figure 2-1 schematically shows the current process flow of sugarcane-derived production in Japan. Sugarcane farming in agriculture and processing in industry have been optimized for raw sugar production. Sugarcane contains sucrose, reducing sugars, other brix (dissolved contents other than sucrose and reducing sugars, such as minerals), fiber, and water. Sucrose is a main content of raw sugar. Reducing sugars and other brix disturb the sucrose crystallization efficiency in cane sugar mills. Fiber deteriorates the yield of brix in squeezing cane juice and is converted into bagasse, which is a residue of sugarcane processing. In general, bagasse is used as a fuel in cane sugar mills to save fossil fuels. Cultivars that contain a higher amount of sucrose and a lower amount of reducing sugars, other brix and fiber have been preferred by the cane sugar mills and chosen by farmers. Agricultural researchers have developed new cultivars by selective breeding to achieve these characteristics. In addition, sugar-rich sugarcane production has been politically supported with subsidies to protect domestic sugar production.



*Elec.: Electricity; HPS: High Pressure Steam; LPS: Low Pressure Steam

Figure 2-1 Current process flow of sugarcane-derived production in Japan.

The byproducts from the cane sugar mills have been dealt with to maximize the benefits from the sugar-rich cultivars. In general, the amount of bagasse generated is more than necessary for sugar production. Figure 2-2 shows the usage of bagasse in Okinawa Prefecture, Japan. More than 80-90% of bagasse has been consumed as fuels in cane sugar mills to save fossil fuels. Surplus bagasse is given away to others (e.g., livestock industry, compost maker) for free or almost free. Because surplus bagasse requires additional cost for storing, it has been difficult to motivate the engineers to save energy. Ash from bagasse combustion and filter cake, which is the filtered sediment from cane juice, are sold to farmers as composts. Molasses is sold to the companies outside the island at more than 1.3 yen kg^{-1} (Okinawa Prefecture, 2016).

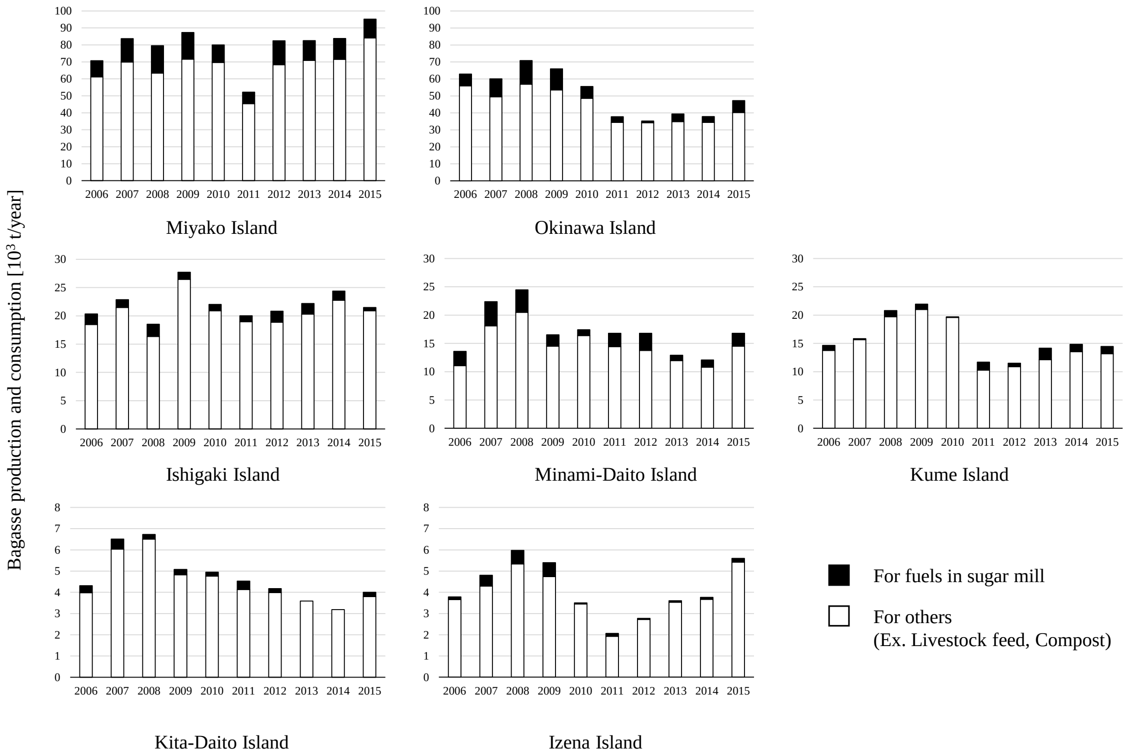


Figure 2-2 Generation amount and usage of bagasse in Okinawa Prefecture (Created from Okinawa Prefecture Department of Agriculture, Forestry and Fisheries, 2017).

The energy flow in the mills has been also designed for sugar production. As can be seen from the case in Tanegashima (Kikuchi et al., 2016b), which is one of the islands in Japan, excess amount of heat is generated and wasted due to a rough heat integration. The electricity demand in sugar mills is also satisfied with bagasse-derived heat via a power plant inside the mills. According to the ratio of required heat to power, a back-pressure steam turbine (BPST), the power conversion efficiency of which is relatively low, has been adopted to all of the Japanese sugar mills.

Conversion of byproducts into value-added ones can be a promising measure to enhance the productivity of sugarcane-derived production. Bioethanol production from molasses as well as selling the excess electricity is one of the most widely-implemented business. In addition, a new sugarcane cultivar that exhibits higher yield per area than the sugar-rich one has been developed as agricultural technology option for combined raw sugar and ethanol production. Ohara et al., (2009) presented that cultivar change to this cultivar could contribute to increases in raw sugar, molasses-derived ethanol and bagasse. Although these cultivars have much impurities that could disturb sugar crystallization in a sugar mill, Ohara et al., (2012) developed selective fermentation, which is a technology of removing impurities before the sugar crystallization, to overcome this demerit.

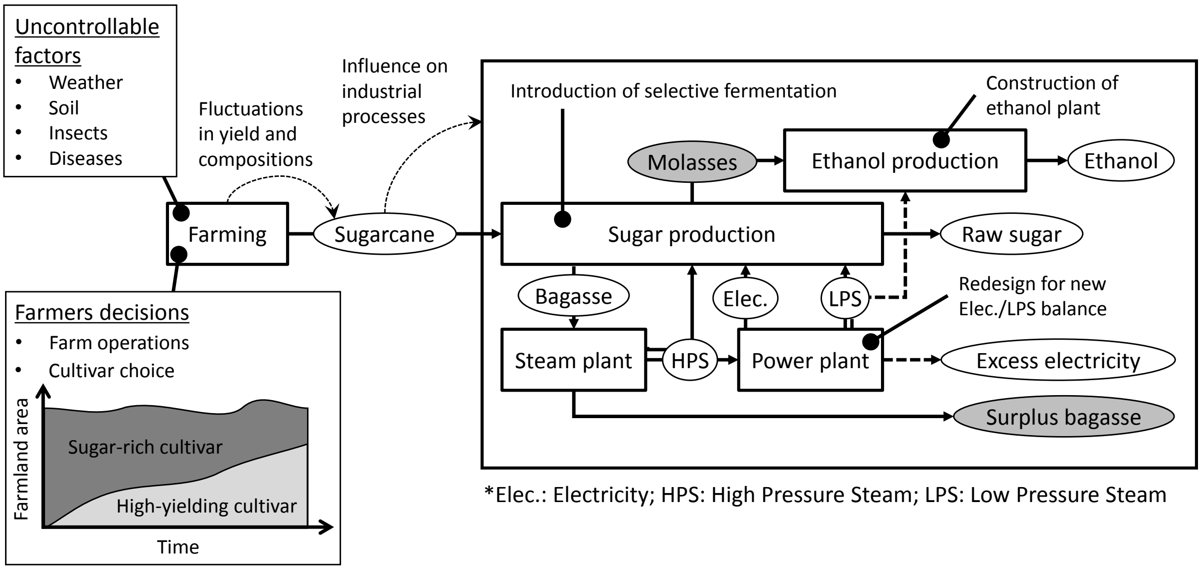


Figure 2-3 Obstacles in transformation of sugarcane-derived production.

In spite of the available technology options, it is challenging for Japanese sugar mills to change existing single line (sugar) to multiple lines (raw sugar, ethanol, electricity). The effectiveness of choosing technology options for the multiple lines in the sugar mills depends on the belongings of the present system such as the current plant design, regulations, relationship with stakeholders, and numerous agricultural factors, which cannot be clearly rationalized. Figure 2-3 shows obstacles in transformation of sugarcane-derived production. Molasses fermentation and electricity selling have not been motivated because the current amount of bagasse generated may have not been enough to provide energy for them. Although the high yielding cultivars may increase bagasse and provide the energy sufficiently, there are four challenges for choosing them. First, there is no way to quantitatively recognize how the cultivar change influences the whole systems. It is challenging for decision makers to judge only based on qualitative discussion. Second, there is no guarantee that sufficient amount of bagasse will be really obtained. Yield and compositions of sugarcane fluctuate influenced by numerous factors such as weather and soil conditions, activities of insects and microorganisms, diseases and farm operations. It is quite difficult to control the amount of bagasse generated within the specific range. Third, the sugar mills do not have an authority over the cultivar of the sugarcane they receive. An unspecified number of farmers choose cultivars as they want. No one knows when and how much the cultivar becomes widespread. Forth, it is difficult to determine the timing of introducing selective fermentation into the sugar mills. The high-yielding cultivars contain much impurities that disturb the efficiency of the sugar crystallization. Although selective fermentation is required to avoid this problem, its economic feasibility depends on the degree of the cultivar diffusion. The cultivar change and the introducing selective fermentation should be planned accordingly.

To sum up, simultaneous design of sugarcane farming and processing is not as simple as the design of chemical processes because of the complex relationship and the difference in time scales, the variety of uncontrollable parameters and uncertainties between agriculture and industry.

B) Rice-derived production

Rice is the third largest staple food in the world behind wheat and corn. Its annual world production is approximately 650 million tons. A line of its production generates a huge amount of byproducts such as rice straw, husk and rice bran, which are the stalks, a shell, and a cuticle between the husk and the grain of rice, respectively. Figure 2-4 shows a rice-processing flow. Paddy is gained with rice straw in harvesting season, followed by shelling and polishing to convert paddy into white rice as a main product and husk and rice bran as byproducts. The production amount of rice straw is estimated as 650-975 million tons (Binod et al. 2010).

An effective use of these byproducts has been promoted for the following two reasons. First, it has been encouraged in terms of sustainability. These are renewable resources obtained in abundance as long as rice maintains its position as a staple food to feed the huge population. Second, it avoids their disposal cost for the polished rice production, which is the main objective of rice farming. Credits from them become a significant additional income for rice producers, while they have to cover the cost of their disposal on their own if the byproducts are not handed over.

There are several ways to consume rice straw, husk and bran. Rice straw is usually incorporated into the soil and the positive effects on the fertility and productivity of soils have been acknowledged in the field of agricultural science (Ponnanaperuma. 1984). Rice husk is mainly used for animal feed, the production of compost and fertilizer or anaerobically digested to biogas (Pfaltzgraff et al., 2013). Rice bran account for 8-10% of the overall amount of the processed paddy rice in weight and is currently used for many purposes taking advantage of its richness in oil, protein, fiber and nutrients essential to life. Rice bran oil is a popular product mainly in Asian countries, such as Japan, India, Korea, China and Indonesia. Edible rice bran oil is used as a substitute for vegetable oils (Sayre et al., 1985; Goenka, 1987), while non-edible oil is used in products such as cosmetics, paints, soaps and detergents (Soares, 1987; Thirumala Rao and Murti, 1961). In Japan, rice bran oil and oleo-chemicals are commercialy produced from rice bran. Biorefinery using rice bran oil has been also proposed (Zaccheria et al., 2015).

Although some rice bran has been already refined and sold as value-added products, those production is below its potential. In Japan, only 40% of the total amount of rice bran generated is processed for rice bran oil production because of its low profitability. Edible oil can be produced from other crops such as soybean and rapeseed. In these cases, the production systems from these crops have been designed only for the edible oil. The qualities of the crops are well managed with the cultivar choice and the cultivation management. On the other hand, because rice bran has been regarded as a byproduct of white rice production, its quality is not much concerned, resulting in decreasing the efficiency of refinery. In the viewpoint of land use, soybean and rapeseed-derived production needs additional farmland while rice-bran-derived production does not as long as white rice is produced. This difference would be an important point considering the limited arable area worldwide, but vegetable oil consumers cannot be aware of it in purchasing.

While the cost-effective technologies for refining has been developed in the industrial field, the most essential obstacle should be the process systems optimized for white rice production. The quality of rice bran is determined by the rice cultivar, farm operations in rice cultivation, and the location and the timing of rice mills. Because rice bran is sharply deteriorated after polishing, only fresh one can be used to produce rice bran oil currently. This limitation makes it difficult to process rice bran at the place where refinery mills are decentralized. Although combined white rice and rice-bran-derived production may give beneficial for every player, there is no way to discuss the alternatives.

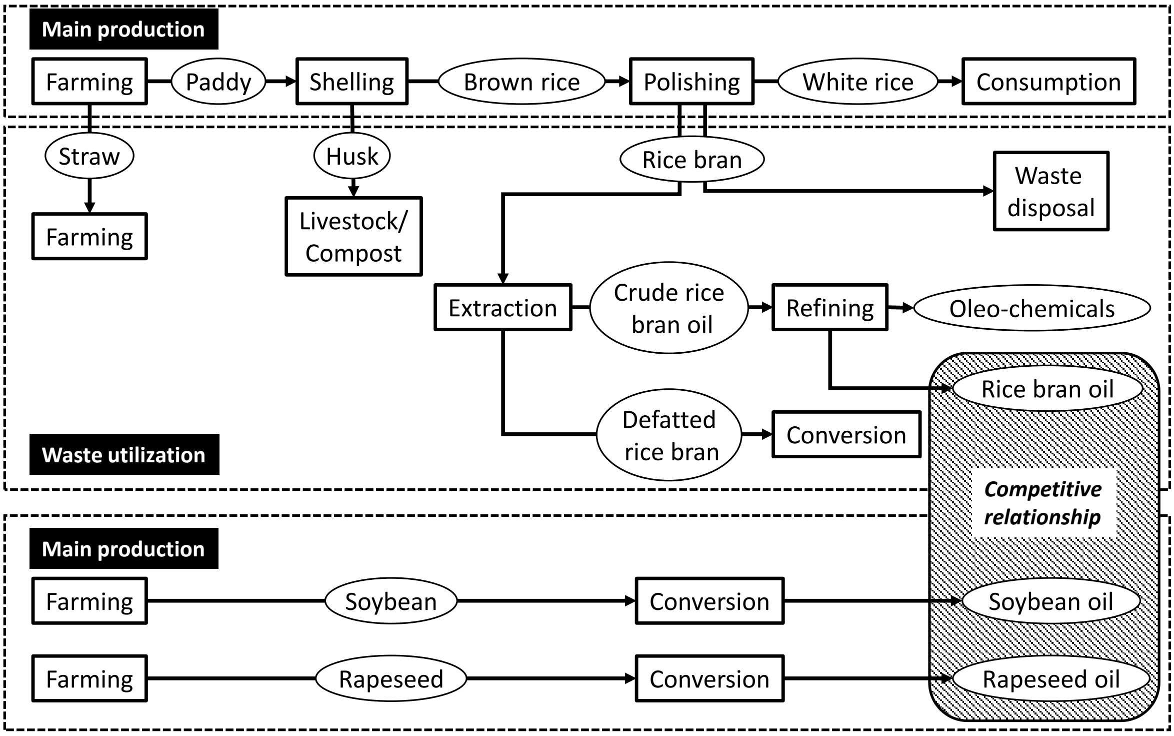


Figure 2-4 Life cycle of rice and its competitive products.

C) Production from plant factories

Plant factories is one of high-yielding horticulture system and have a potential of farming vegetables. They can be categorized into two types according to the light source: plant factories with sunlight (PFSLs) and plant factories with artificial light (PFALs and referred to Kozai et al., 2015). PFALs enable mass production of vegetables with the control of their growing environment such as light intensity, temperature, water, CO_2 concentration in the air and nutrients concentration in the water.

In Japan and other Asian countries, leafy greens, herbs and transplants are produced. Kozai et al. (2015) addressed the merit of PFALs as follows:

a) The factory can be built anywhere without being bothered by solar light and soil availability;
b) The growing environment is not affected by the climate and soil fertility outside the factory;
c) Year-round cultivation is possible;
d) The productivity per area is more than 100 times higher than that of open-field cultivation;
e) The quality of product is more operational with the control of the growing environment such as light quality compared with that in open-field cultivation;
f) Consumers do not have to wash the product before eating because it is pesticide-free
g) Produce has a longer shelf life because the bacterial load is extremely low compared with field-grown product;
h) Energy for transportation can be saved by building PFALs near urban areas; and
i) The factory can use resource such as water, CO_2 and fertilizer in high efficiency with minimum emission of pollutants to the outside environment.

Because it may create a new market in addition to the above merits, some countries position the promotion of plant factory as an economic growth strategy (Anpo et al., 2015).

To implement PFALs, a lot of engineering researchers have invested their efforts in the development of the cost efficiency technology such as the light sources, air conditioners, air circulation fans, CO_2 and nutrient solution supply units, an environmental control unit, and automation devices for handling operations (Kozai et al., 2015). Utilization of waste heat from other industries has been also considered as a strategy to reduce the cost (Togawa et al., 2014). Incorporating Information and Communication Technology into PFALs has been another approach to the enhancement of the feasibility (Anpo et al., 2015). Some agricultural researchers has developed a crop that produce a value-added protein in PFALs via breeding (e.g., Kato et al., 2010).

Despite the contribution to the public benefit and many research investments, it is challenging for PFALs to take part in the existing market, which open-field cultivation has already occupied, in terms of the production cost. Figure 2-5 shows the price of lettuce for month in three Japanese cities. The market price of lettuce fluctuates throughout the season. In Sapporo, the maximum price in 2012 is more than six times larger than the minimum. This is because the market price is strongly influenced by the supply from open-field cultivation. While the supply from the open-field cultivation is relatively small because of the seasonality or the unseasonable weather condition, a plant factory can sell the vegetables in high prices. However, once the price drops, the plant factory will be in deficit under the current technological level.

The difference in the function between PFALs and open-field cultivation is overlooked in the market. As mentioned above, they are different in the quality of the vegetables produced such as shelf life, taste and nutrients and the utility consumption. Furthermore, the role of protecting food security is not reflected in their values in spite of the important factor for consumers.

Because there is no guarantee that open-field cultivation can always stably supply crops in low cost, it should be good for the public to introduce PFALs. However, there is no incentive for anyone to change this situation as long as all decision makers make decisions rationally in their personal range. Open-field farmers produce vegetables as they have done without being strongly affected by the plant factory business. Consumers generally seek for less expensive vegetables in every season. Policy makers give open-field cultivation tax benefits to protect domestic agricultural production. Entrepreneurs try to start business under such situation.

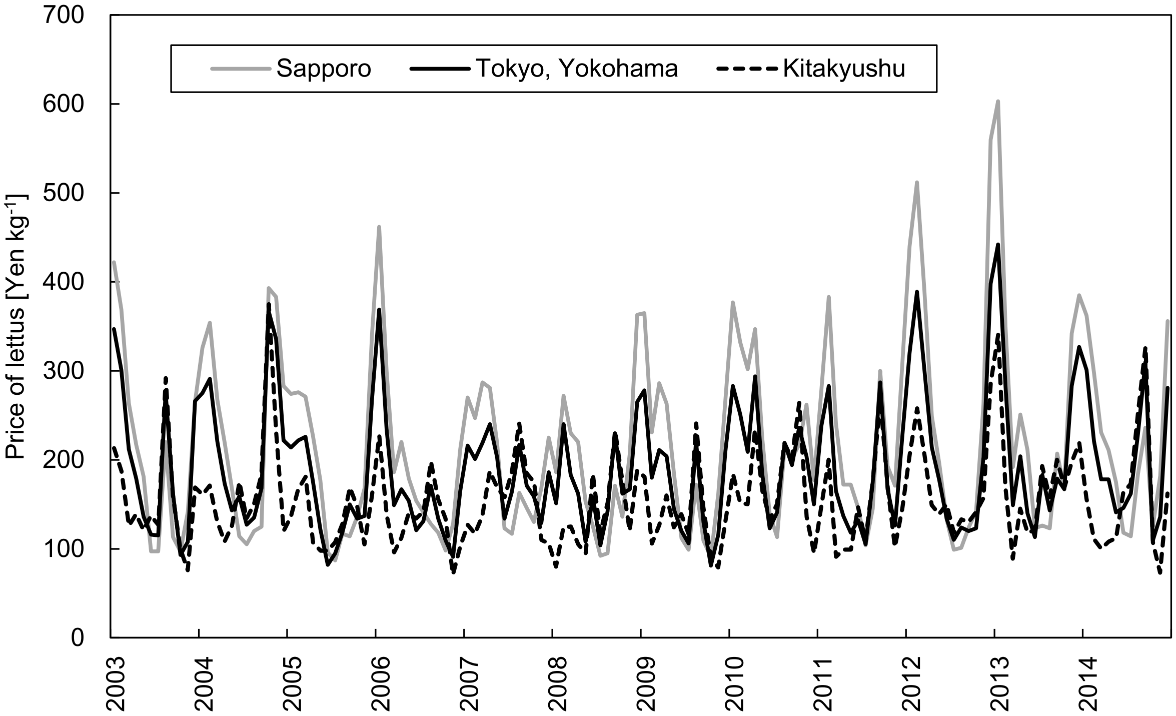


Figure 2-5 Price of lettuce for month in Sapporo, Tokyo, and Kitakyushu (Created from MAFF, 2003-2014).

2.1.3. Systemic Problems in Systems of Agriculture and Industry

It is hard to solve the three problems explained above based on the reductionism approach. In the case of sugarcane-derived production, if the environmental conditions were freely controlled, its relationship with the yield and compositions would be systematically analyzed with the collection of sufficient data. However, the number of uncontrollable parameters far exceeds that of controllable in agriculture. It is meaningless to spend much time on collecting data for solving urgent problems.

In the case of rice-derived production, if the amount and quality of the rice bran are controlled, it should be easier to produce rice bran oil and oleo-chemicals. However, it is hard to analyze which factor affects them.

In PFALs case, if the timing of the bad crop can be predicted, it would be easier to introduce PFALs. However, the yield is greatly influenced by uncontrollable factors such as weather conditions on open-field cultivation area. There is nothing for it but to wait until the technological level sufficiently rises.

There are some cases where the efficiency of farming and processing is significantly enhanced through increasing in their scales. However, such solution is merely a solution applicable to special conditions. Table 2-1 shows the characteristics of cases suitable and unsuitable for large-scale farming. Many kinds of industrial and food crops are suitable for large-scale farming in that they can be harvested by agricultural machinery, while most of horticultural crops are unsuitable because of their delicacy. The area of flat land is limited over the world. Historical aspects of the target farmland such as landowner culture in Japan have to be taken into account. In the Japanese case, it is hard to integrate individual small farmland to produce larger one probably because of owners' emotional reason. According to Lowder et al. (2016), 85% of farms are smaller than 2 ha in 2013. The method of renovating small and middle scale farming is strongly needed.

Table 2-1 Characteristics of cases suitable and unsuitable for large-scale farming

	Suitable case	Unsuitable case
Agricultural machinery	Harvestable by machinery (Industrial crops, Food crops)	Delicate crops (Horticultural crops)
Landform	Flat land	Mountain, Hill
History	Reclaimed land	Landowner culture

There have been problems that one's decision unconsciously limit others' decisions, degrading systems performances or disturbing adaptation of systems to the new environment like the three examples. In these situations, the causes vary and are hardly identifiable. Such problems are called as systemic problems in this thesis. Lexical meaning of "systemic" is: affecting or connected with the whole of something, especially the human body (Oxford Advanced Learner's Dictionary of Current English, 7th ed.). Figure 2-6 schematically represents the difference between systematic and systemic. Systematic is based on reductive reasoning where a problem can be attributed to some causes and their relationship can be explicitly explained. This way of thinking cannot be applied to systemic phenomena where a problem cannot be explicitly attributed to causes. There are apparently relationship among those causes and problems but each cause is not to blame.

Compared to fossil-derived production, plant-derived production tends to arise systemic problems because of the difference in characteristics between agriculture and industry. Figure 2-7 shows the major four differences between agriculture and industry.

In factories, raw material is converted into other products inside the building, which entirely blocks the intervention from the nature. Although some uncertainties arise in thermodynamic, kinetic, and other parameters in chemical industries (Ahmed and Sahinidis, 1998), they greatly reduced uncertainties and enhance the controllability of process operations with the building materials. On the other hand, agricultural crops are cultivated outside the building except in the case of plant factories, and exposed to the natural risk factors such as weather, soils and diseases. In addition, plants have the complex growth mechanism based on life science that fossil fuels are little related to. As a result, the gap in the degree of uncertainties arises between agriculture and industry.

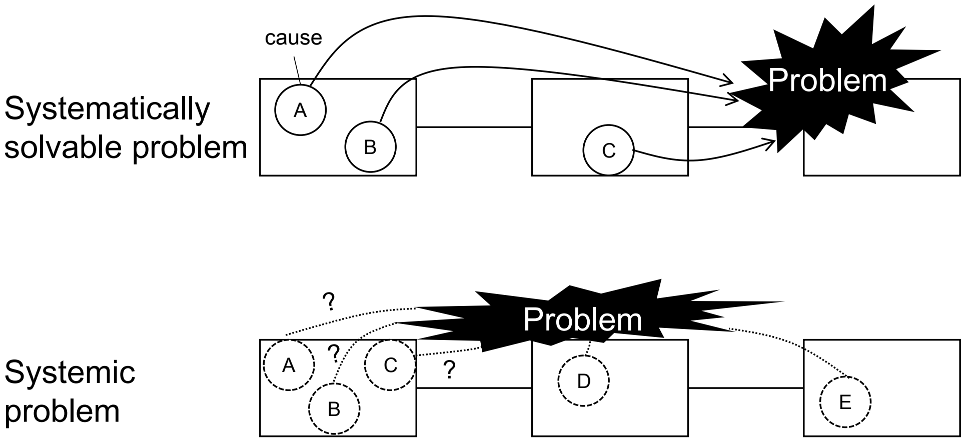


Figure 2-6 Difference between systematic and systemic approach.

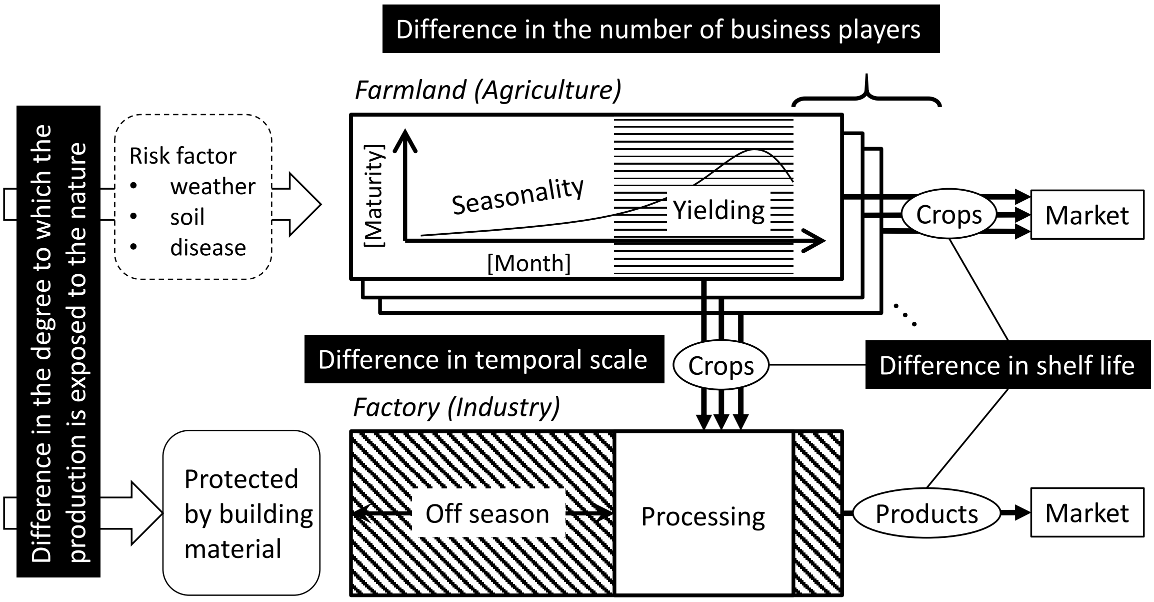


Figure 2-7 Major differences between agriculture and industry in plant-derived production.

This gap has caused the difference in the way of system design. While systematic methods of chemical process design have been developed based on both quantitative analysis and heuristics, decisions in agriculture greatly have depended on heuristics. This could be because the magnitude of uncertainties is far beyond the predicted range and little meaning or importance of quantitative discussion have been found in agriculture.

Temporal scales are also remarkable difference between agriculture and industry. The plant growth has a temporal range from raising seedling or planting to harvesting. It takes several months or a year to harvest matured agricultural crops. Combined with the abovementioned difference in the exposure to the nature, this temporal range leads to the seasonality of agriculture as demonstrated in Figure 2-8. The season when the crops are matured is limited within several weeks or months of a year. In addition, the maturity describes a parabola during the season with fluctuation. These characteristics are unique to agriculture and technically make it difficult to discuss with industry quantitatively.

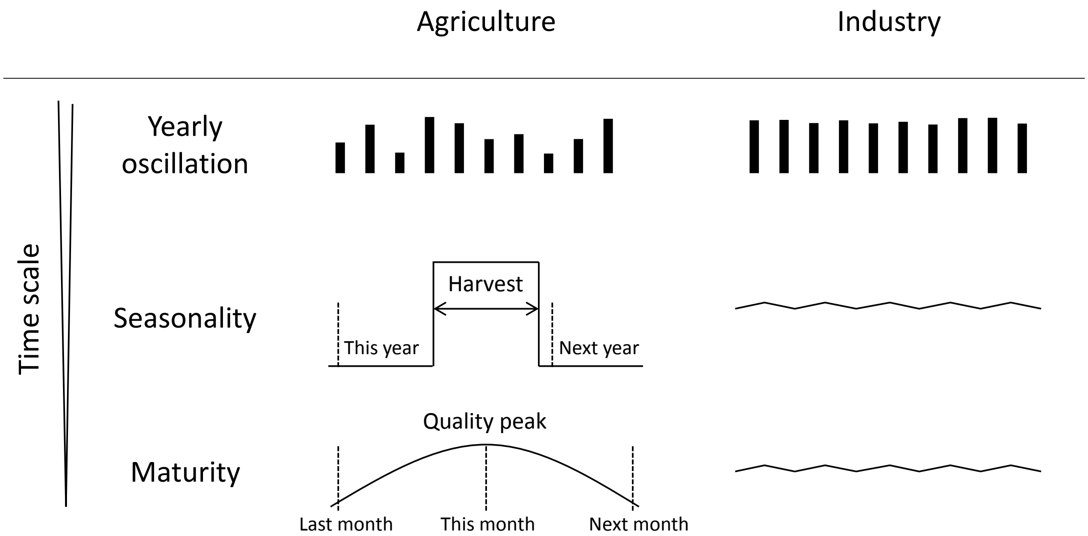


Figure 2-8 Difference in temporal scale between agriculture and industry.

Plant-derived resources have relatively short shelf lives unlike fossil-derived products or industrial products. In general, their compositions continuously change because of biological activities or catalytic reactions of enzyme. Their bad shelf stability gives a stress on the downstream industrial processes.

The number of business players is different between agriculture and industry. In contrast to industry, there are an unspecified large number of farmers in agriculture. Some may produce crops as usual and others may produce other crops or stop farming. Some new comers may enter the market as farmers. The decisions are made independently and little controllable from other stakeholders. Aggregation of decision makings would be difficult even within farmers.

These differences has posed three challenges as follows. First, it is difficult for the players to recognize the problems. One's decision may cause others' problem at a faraway place. If the cause and effect relationship goes across agriculture and industry, expertise in multiple fields will be required to solve the problem. A time lag between the decision and the revelation of the problem further obscures the responsibility. Decision makings in planting crops will have an influence on the industrial processes after harvesting. This time lag is peculiar to agriculture.

Second, it is hard to analyze the cause and effect relationship even if players recognize the problem. Monthly or yearly time scales and uncontrollable factors such as weather and soil conditions blur the relationship among parameters. If there is an eternity of time, experimental results might be collected enough to analyze the relationship. However, available time is limited and prompt actions are needed for many actual problems. There has been nothing for it but to partly rely on heuristics, resulting in lowering the value of quantitative discussion.

Third, building consensus among multiple decision makers would be a hard task even if they know what they should do for the whole system. Farmers and engineers as well as other stakeholders may be responsible for the design parameters. The conflict of interests may be obstacles to implementation of the measure.

Considering these challenges, it should be hard to solve systemic problems only based on a reductionism approach. Because it is difficult to clearly define and structure systemic problems, players just vaguely recognize the problem, making it hard to build consensus among players. A new methodology that moves forward from reductionism is required.

2.2. Concept of Systemic Intensification

Since plant-derived production involves many stakeholders including both agriculture and industry, the situation where all aspects of interest for every stakeholder become better should be sought under the constraints from externals such as climate conditions, regulations, values of products, technological levels, etc. In addition, if such situation could be expected no longer, the explicit request should be conveyed to appropriate decision makers to modify the constraints and promote the alternative generation. In this thesis, the transition from the current to such desirable systems is defined as intensification, although its exact definition depends on research fields.

Systemic problems are obstacles to intensification of agriculture and industry in plant-derived production. They are caused by systemicity, which is a complex and dynamic behavior exhibited by systems or systems-of-systems. The behavior of the whole system cannot be attributed to its parts on such systems. According to Checkland and Scholes (1990), systemicity can be interpreted from two pairs of its core concepts: emergence and hierarchy, communication and control. Emergence is the properties that have no meaning in terms of the parts but exhibit meaning as a whole. The emergence property could come from hierarchical structure that consists of different spatial scales of layers. While these two properties represent the behavior derived from systemicity, communication and control help them adapt to the environmental change.

Systemicity of systems in real world has been controversial in many fields. In the medical field, the systemicity of body has been studied. Systemic disease is one of the examples that represents its systemicity. It affects a number of organs and tissues, or affects the body as a whole but is hard to be eliminated. The economic field has discussed systemic risk, which is the possibility that an event at the company level could trigger serious financial instability worldwide or collapse of an entire industry or economy. With regards to social safety issues, Taniguchi (2015) warned that attention should be paid to the risk with systemic nature of the current complex social system from interdisciplinary perspective in response to the accident at the Fukushima nuclear power plant in 2011. In business field, Chebrough and Teece (1996) proposed systemic innovation, which is brought about by involving the complementary innovation in the relevant system accordingly, as a strategy of successful business.

Plant-derived production could be systems with systemicity. Appropriate communication within the systems is important for the adaption to the environmental change. Nevertheless, the current communication between agriculture and industry is not enough, resulting in the ad hoc design from the individual viewpoint. They may have lost their chance to shift to better conditions. In other words, the methodology for the appropriate communication among players has a potential of evolving the systems seamlessly.

Based on the above discussion, *systemic intensification*, is proposed as a systems design approach to achieve intensified systems through untangling systemic problems. Systemic intensification in this thesis is distinguished from other previous approaches in terms of cooperativity and shade of gray (Karplus, 1976) that indicates the explicitness of phenomena as shown in Figure 2-9. In general, the goal of a systematic approach (that is used here in the narrow sense) is to create a white box model (Karplus, 1976) of the phenomena related to the problem, that is, to completely reveal the relationship among all related parameters. In this case, a collaborative approach would be easier because the responsibility of the problem can be determined in the objective way. However, this situation is far from realistic. In reality, problems have to be dealt with admitting that uncertainties cannot be completely removed under the available time and resources. For example, chemical engineering is an academic field that has an aspect of creating white box models of chemical reaction for industrial progress. Although there is a limit of elucidating the phenomena, the knowledge acquired and stored up to date has been applicable to the economically-beneficial process design and operation. In addition, the mixture of such explicit and implicit knowledge has contributed to enjoying further benefits through industrial symbiosis, which is one form of collaborations between multiple chemical plants.

Many farmers in small or middle scale farming highly depend on their individual empirical knowledge. While there remain black box models to some extent in farming regardless of its scale, large-scale farming could be sometimes achieved in a collaborative way if it satisfies some special conditions especially in Table 2-1.

Figure 2-10 shows the current situation of plant-derived production. Many black boxes are left here and every player makes decisions from their own point of view. There should be room for elucidating the behavior of plant-derived production system by collecting data and knowledge from all related fields. Although the limit of the elucidation would be seen considering allowed time and available resources, the resolvable range would be expanded toward the “collaborative” direction with a bit of ingenuity. In this way, systemic intensification is defined in this thesis as an approach for intensifying systems through involving and collaborating with appropriate players under the situation that cause-and-effect relationship is not necessarily clear. The method of specifying and expanding the slashed area in Figure 2-10 has to be established for achieving systemic intensification.

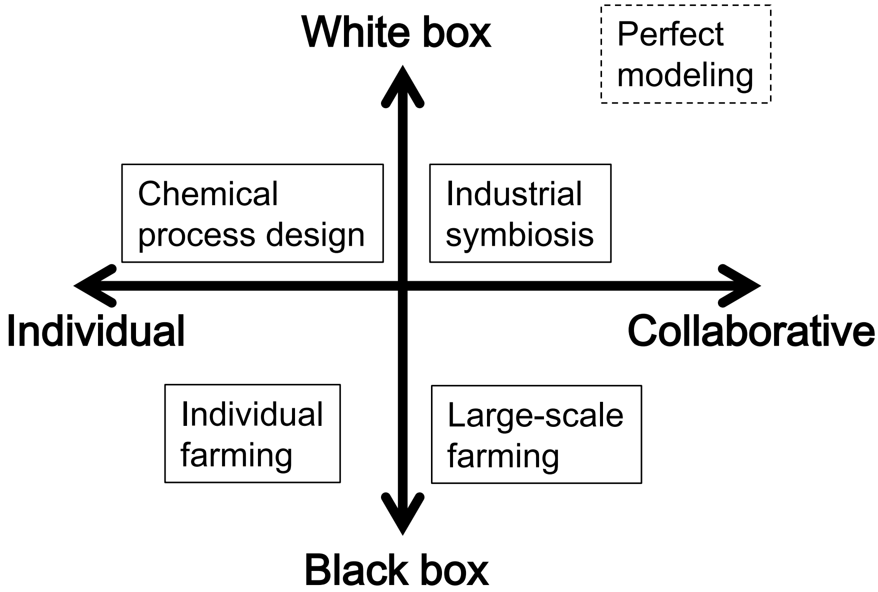


Figure 2-9 Mapping of problem-solving approach in terms of cooperativity and shade of gray that indicates the explicitness of phenomena.

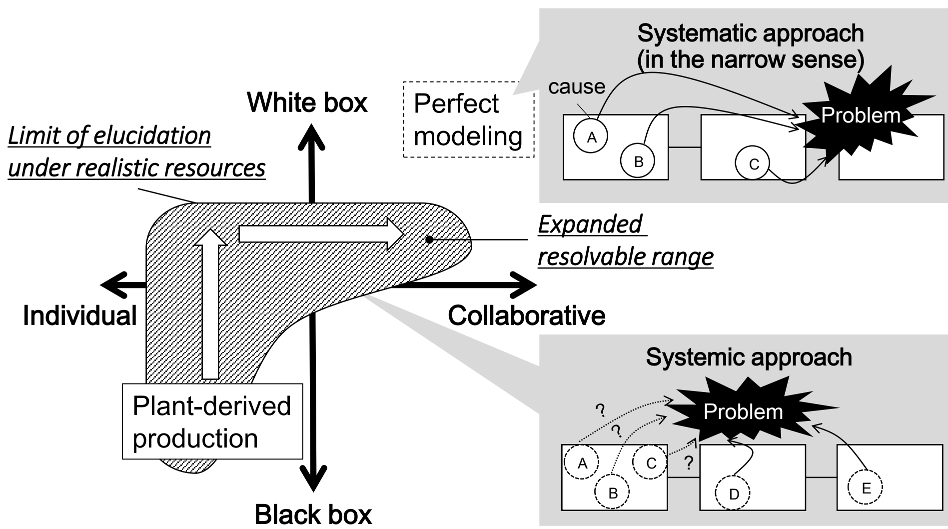


Figure 2-10 Mapping of proposed "systemic" approach for intensifying plant-derived production in terms of cooperativity and shade of gray.

Figure 2-11 illustrates the role of a communication tool in systemic intensification. First, a tool is developed to quantitatively analyze mass and energy flows through plant-derived production by making full use of available data and knowledge. The effects of both agricultural and industrial options on them can be analyzed on this tool. Then, with the use of this tool among decision makers in both agriculture and industry, they could get better understanding of how their decision on the whole system. Finally, the tool is used for searching better alternatives and scenarios for reaching them on their meeting. Until the present, agriculture and industry have been searched for alternatives regarding only their own option as variable and, therefore, the search space is restricted by others' decision makings. Synergy effects may be displayed with the tool if both agricultural and industrial options are combined. In this time, the search space of alternatives expands and may contain some alternatives that move the group of the Pareto-optimal index forward. In other words, both agriculture and industry could be intensified by manipulating both options. Although there is no guarantee that the tool exactly reflects the behavior of the real systems, it should be a strong tool to support their planning for the future actions.

The actions described above should be repeated through the life cycle of agriculture and industry because external factors such as social and environmental conditions and available technology options continue to change. Mechanisms required for activating these actions are discussed in the next section.

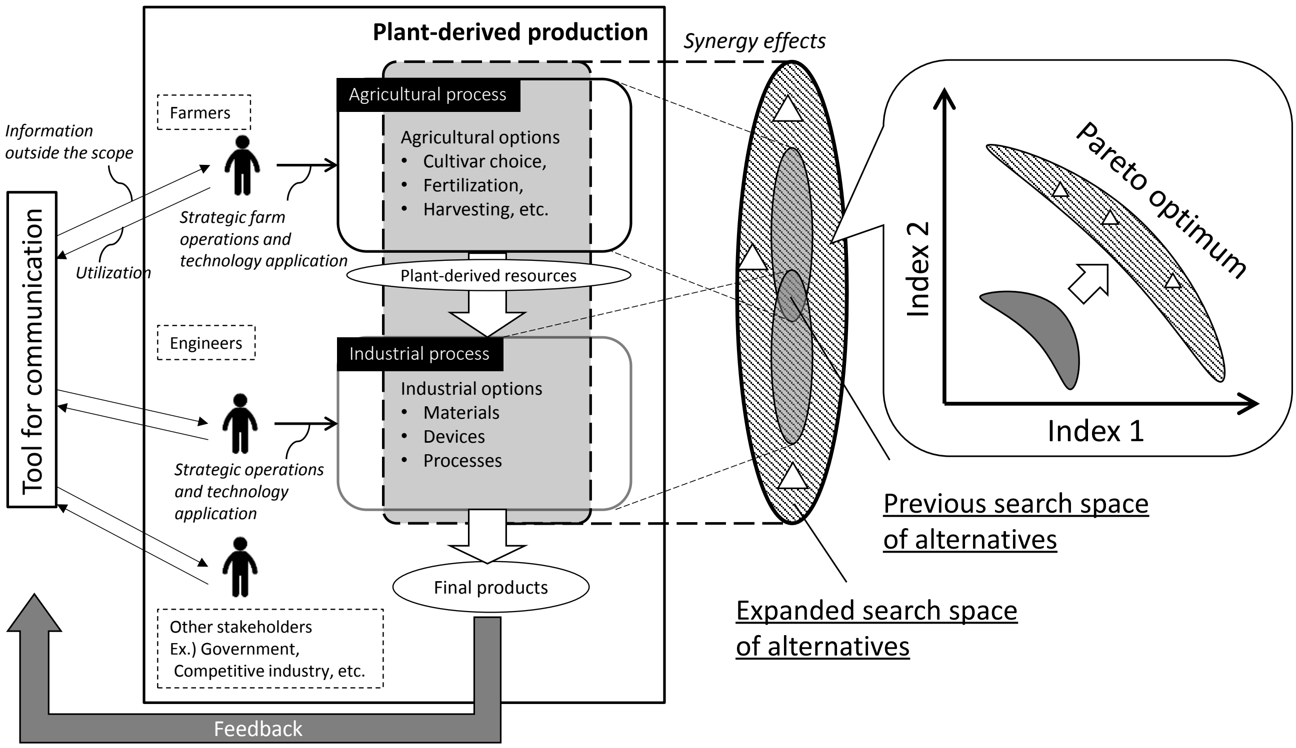


Figure 2-11 Role of communication tool in systemic intensification.

2.3. Requirements for Systemic Intensification

Requirements for systemic intensification of agriculture and industry on their life cycle stages are explained in this section. Figure 2-12 shows the lifecycle of farmland, plant factory, factory, and plant-derived resources. At the beginning, research and development provide available technology options in both agriculture and industry. Utilizing available options, preparation of field, cultivation and yielding are conducted in agriculture and factory construction and operation are done in industry. Although these design stages are crucial to the system performances, the communication between agriculture and industry is in short. Mechanisms should be developed to promote the communication for systemic intensification. Three required mechanisms are proposed below.

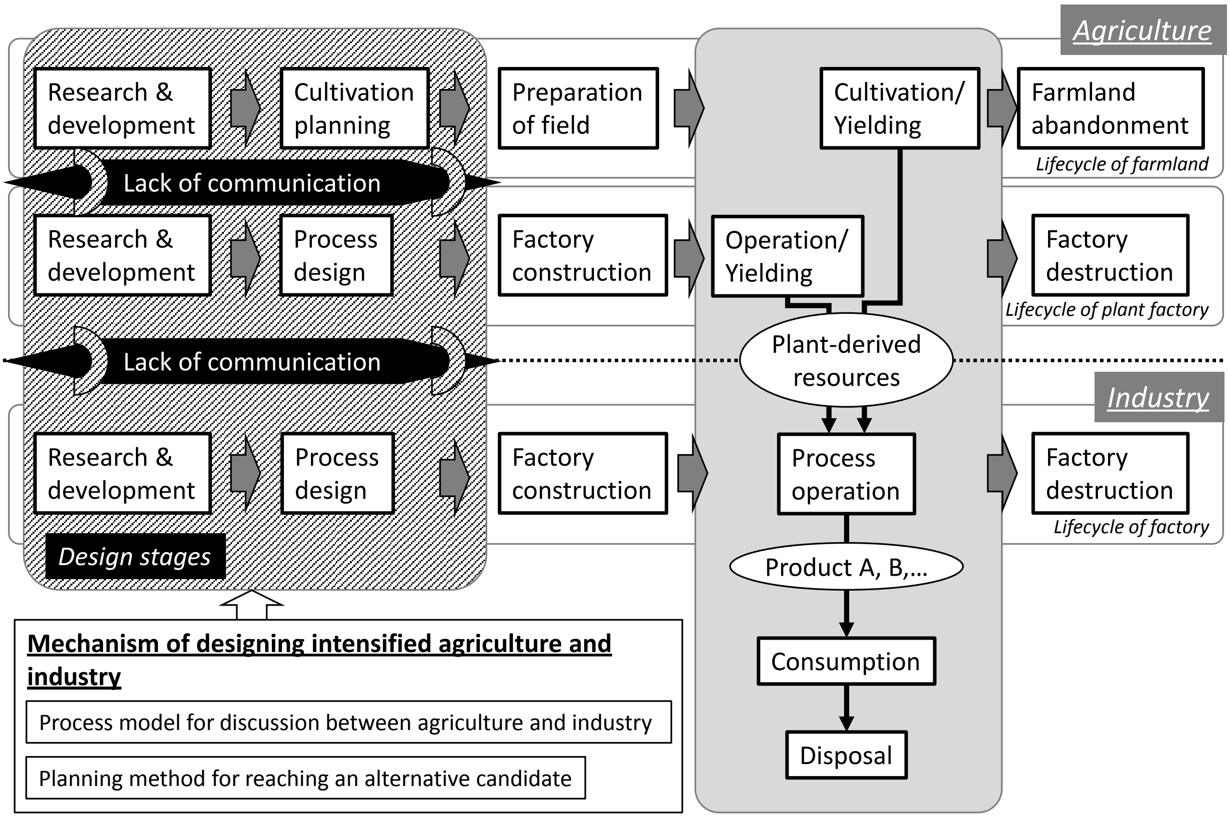


Figure 2-12 Lifecycle of farmland, plant factory, factory, and plant-derived resources and required mechanism of systemic intensification in plant-derived production.

2.3.1. Process Model for Discussion between Agriculture and Industry

The technical knowledge in every field is essential to appropriate interpretation of problems that lie across multiple fields. However, it is challenging for players that constitute the systems to master all the related knowledge. A modeling approach has played a role in converting complex phenomena into easily understandable media to discuss quantitatively and to look for the desirable configuration of the system. Such approach may contribute to facilitating the communication among a variety of players.

The aim of the required model is to support preliminary feasibility analyses of the implementation of agricultural and industrial technology options and the identification of solutions that are beyond the scope of local technological improvements. The potential users of the model are actual decision makers. It is expected that agriculture and industry in plant-derived production will be intensified by dramatic enhancements of synergy effects between technology options in both areas. The functional unit (FU) used in the model should be carefully specified to conduct static analyses considering the difference in temporal scales between agriculture and industry. By associating applicable technology options in agriculture and industry with the indicators through the modeling, the designers of target systems can acquire instructive information from these static analyses via the model. The options can then be adopted as inputs to the model. Eventually, an integrated model should provide users with new types of motivation and create a paradigm shift in the support of the seamless intensification of plant-derived production.

The model do not have to completely follow the rigorous physicochemical model because this concept is based on holism, where it is hard to predict the phenomena exactly. Establishing the elaborated model by making full use of available data and knowledge and simplifying moderately under the limited time would be a challenge in this study.

2.3.2. Planning Method for Transition to Intensified Agriculture and Industry

There is a high possibility that alternatives generated from the above static model request multiple decision makers to modify their options simultaneously. It is not until all decisions are made that they can benefit from the alternative implementations. A single decision may not be motivated in some cases. As one's decision potentially affects others' decision and the interests of the different stakeholders may conflict with each other at times. Such conflict may emerge as an obstacle to the intensification.

In addition, it takes years of time to transit to the alternative system in many cases, especially in agriculture, while the situation could change from the present. As time passes, the society changes in laws, regulations, prices of products, values for people, etc. Most changes are uncertain but some may be predictable. How to transit from the present system to the alternative system should be discussed carefully making full use of available resources. Therefore, a planning method for transition to intensified agriculture and industry should be developed.

2.3.3. Framework for Systemic Intensification

The two mechanisms proposed above may not be practical without helps of experts and researchers. However, it is not realistic to involve experts and researchers every time to solve problems considering an infinite number of plant-derived productions. In general, it is difficult for experts and researchers to recognize where they can make the most of their knowledge and skills. A framework is required as a mechanism that enables actual stakeholders such as farmers and on-site engineers to involve experts and researchers on their own as necessary.

2.4. Summary

Actual problems in three cases, i.e., sugarcane-derived production, rice-derived production and production from plant factories, were analyzed to examine the required concept of systems design in plant-derived production. As time passes, the requirements on the existing systems from externals, the relationship between producers, values of products and available technology options has changed. Nevertheless, one decision maker have unconsciously restricted others' decision and it is becoming difficult for the systems to change. There have some systemic problems that cannot be attributed to one cause and that a single decision maker cannot solve in plant-derived productions. The reason of the systemic problems could derived from the three challenges derived from the differences between agriculture and industry, i.e., difficulties in recognizing and analyzing the problems and in building consensus among stakeholders.

"Systemic intensification" was proposed as a concept of systems design to untangle the above systemic problems in plant-derived production. According to this concept, the appropriate collaboration between agriculture and industry in systems design stages can enable to expand the search space for alternatives and generate competent one that has not been found in the previous way.

Three mechanisms required in systems design stages are proposed to achieve systemic intensification. First, a process model is needed to enable agriculture and industry to communicate and discuss quantitatively. Second, a method for planning the systems transition considering time scale and future uncertainties is required to avoid the conflicts of the interests between stakeholders in advance. Finally, a framework for providing the two mechanisms addressed above has to be developed for on-site decision makers to conduct systemic intensification practically. These mechanisms are developed in Chapters 3-5 through actual case studies.

Chapter 3. Integrated Modeling of Agricultural and Industrial Processes: A Case Study of Sugarcane-Derived Production

3.1. Introduction

A method of analysis integrating agricultural and industrial processes is developed in this chapter. Figure 3-1 shows the overview of this chapter. As addressed in Chapter 2.3.1, it is difficult for agriculture and industry to design systems considering the other side because they lack a tool for quantitative discussion between agriculture and industry. Although there should remain data and knowledge over agricultural and industrial fields, the behavior of the whole system has been far from a white box model (see Chapter 2.2). Modeling agricultural and industrial processes in an integrated manner could make it possible to discuss quantitatively between them. In Chapter 3.2, the method of integrated modeling of agricultural and industrial processes is verified as a mechanism to support the alternative generation through the case study of combined sugar and bioethanol production from sugarcane.

When a new technology is applied to the systems, its merit may be impaired unless the effects of the introduction on the whole systems are sufficiently reviewed. At this time, it is challenging for the developers to consider how the agricultural technology affects the efficiency and decision makings in industry and how the industrial one affects those in agriculture because both technologies have been apt to be discussed within each field individually. Modeling the technology and analyzing it together on the model developed in Chapter 3.2, how the technology affects the systems and how the required technology is like could be examined. In Chapter 3.3, selective fermentation is chosen as an applicable technology on combined sugar and ethanol production and its influence on the systems is analyzed. In addition, the function of this approach as generating new technology requirements is observed.

Plant-derived production sometimes receives requests from other industries or facilities in its surrounding area. These requests have not always met with under the situation that the alternative is generated within either agriculture or industry. However, the collaboration between agriculture and industry could sometimes enhance synergy effects and offer alternatives for the request. In Chapter 3.4, it is verified whether the modeling approach can generate new alternatives considering the request from power companies to cane sugar mills.

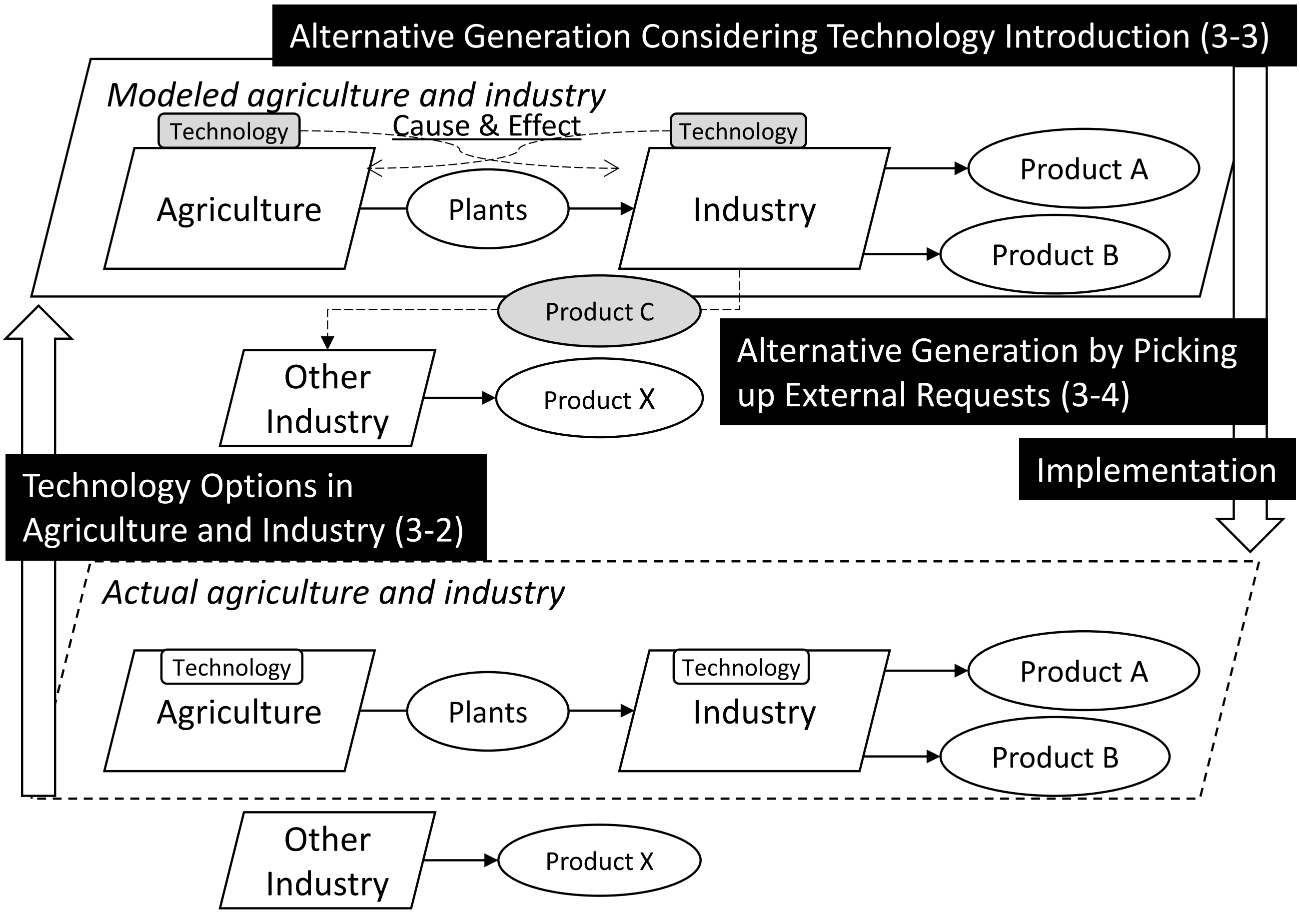


Figure 3-1 The overview of Chapter 3: Development of model integrating agricultural and industrial processes and discussion about applicable technology considering external demands on it.

3.2. Technological Options in Agriculture and Industry

3.2.1. Background of Cane Sugar Industry

As discussed in Chapter 2.1.1, most sugarcane industries have utilized sugarcane cultivars that were bred and selected for sugar extraction alone: The cultivars have high sucrose levels in their juice, as well as generally preferable characteristics, such as high yield and good disease tolerance. The sugar mills have been designed primarily to maximize the profit from sugar production. The juice is heated, purified, and concentrated before consecutive extraction by crystallization with centrifugal separation in the same way as most cane sugar mills worldwide. Minimizing sucrose loss in the molasses, using sugarcane that has high sucrose composition (among other components, such as glucose, fructose, and minerals) is important, as components other than sucrose inhibit its crystallization. Molasses was not utilized effectively before it was recognized as a raw material for ethanol and other chemical substances. In general, cane sugar mills obtain most of their heat and electricity requirements for the abovementioned processes from the fibrous residue (bagasse) obtained after pressing cane (Amorim et al., 2011).

Recently, higher expectations have been imposed on the sugarcane industry. Application of heat and electricity cogeneration to supply energy utilities for the grid or local industries is one example (Guerra et al., 2014; Kikuchi et al., 2016b). Another is the supply of liquid fuels. Either sugarcane juice or molasses can be utilized as a feedstock for producing ethanol, which can replace fossil fuels for vehicles either by dehydration (Macedo et al., 2004; Macedo et al., 2008; Nguyen and Gheewala, 2008; Kim and Dale, 2006; Ometto et al., 2009) or by further conversion into fatty-acid ethyl esters. Chemicals such as ethylene and ethyl acetate can also be produced from ethanol (Kikuchi et al., 2013; Nguyen et al., 2011). However, these new expectations are not met in some regions (e.g., Japan) because the industrial structure for both farmers and sugar mills has been directed toward only sugar production. To conduct additional production in sugar mills, additional energy is required, which can generate requirements for fossil fuel inputs to the mills.

Meeting these expectations beyond what is currently available is possible if the biomass resource exploitation strategies and conversion processes are consistently revised according to the new production objectives. For example, Ohara et al. (2009) demonstrated that by choosing an unconventional cultivar that has significantly greater yield than the current mainstream cultivar, combined with process modifications, a factory could produce equivalent raw sugar with an eightfold increase in ethanol production in a case study based on data from Ie Island of Okinawa in Japan. The cultivar assumed here has more reducing sugars (i.e., glucose and fructose) in the juice (Sugimoto, 2000). It also has a much higher fiber ratio. Neither of these characteristics was favorable for the conventional objective of minimizing the production cost of sugar extraction. However, the increased fiber was used to generate the energy required to produce anhydrous ethanol. Sucrose crystal separation was conducted only once instead of three times: the second and third extractions would have been more difficult because of the lower sucrose content. Nevertheless, the raw sugar productivity was maintained at the same level, because the total productivity of the sugarcane increased.

Such promising approaches have not yet been put into practice. Instead, much effort has been devoted to improving unit processes, such as fermentation (Basso et al., 2008; Sridhar, 2011) and distillation (Zeng and Li, 2015), or to pursuing feasible pathways within engineering fields (Andiappan et al., 2015; He and You, 2015). Compared with fossil fuel exploitation and extraction, much fewer studies of biomass resource exploitation and extraction have been performed, in spite of the considerable influence of agricultural factors on the quantity and quality of biomass. This might be a result of a wider gap between the disciplines of agriculture and manufacturing compared with the gap between mining and manufacturing. Simulation-based preliminary analysis should play an important role in compensating this gap. In the following section, the requirements of process model are defined, followed by its development.

3.2.2. Requirements Definition of Process Model

Requirements definition

In this section, a process model supporting static analysis was developed on the case study of sugarcane-derived production. The proposed model should enable preliminary feasibility analysis of modifications of sugarcane processing from cultivation to raw sugar and ethanol production at sugar mills. All existing cane sugar mills are targeted for modeling although there are various types of the mills all over the world as shown in Table 3-1. Not all sugar mills produce ethanol and electricity but the basic structure of sugar production processes is common to them. A basic input/output analysis using life cycle assessment (LCA) can be a strong support for the designers of combined sugar–ethanol production considering novel technology options, e.g., new sugarcane cultivars. The functional units (FUs) of the model can be defined as production units; e.g., farmland area with cultivation period, i.e., $(\text{area})^{-1}\cdot(\text{time})^{-1}$, for sugarcane planting. Based on the FUs, static analyses of selected sugarcane-planting regions with sugar mills can be conducted with or without applicable technology options in agriculture and industry. The total yields of products, environmental impacts, and other related performance indicators can be evaluated for the target region.

Table 3-1 Type of existing cane sugar mills classified by final products

Type	Raw sugar	Ethanol (from molasses)	Electricity	Main area
Ⅰ	○			All Japanese cane sugar mills
Ⅱ	○	○		Southeast Asia
Ⅲ	○		○	Thailand, Philippines
Ⅳ	○	○	○	Thailand
Ⅴ	Raw sugar or Ethanol (from cane juice) + electricity			Brazil

The relationships between agricultural and industrial processes should be described using mathematical equations. The main interconnection stream between them is sugarcane, the quality of which is defined as the annual yield per unit area—e.g., [(t-cane) $(\text{ha})^{-1}$ $(\text{year})^{-1}$] or [$(10^3$ kg) $(10^4$ m$^2)^{-}$

^{1} (year)$^{-1}$]—and its composition of sucrose, reducing sugars, other brix (dissolved contents other than sucrose and reducing sugars, such as minerals), fiber, and water. Based on the process and the operating parameters of the agricultural process, these values for sugarcane must be estimated by the model developed in this study. At the same time, the quality of the sugarcane must be related to the performance of the industrial process. Raw sugar and ethanol are the main products of the industrial process. Both sucrose and reducing sugars are the raw materials for ethanol, while reducing sugars inhibit the crystallization of sucrose (van Hook, 1946). This means that increased amounts of reducing sugars result in increased ethanol yield instead of decreased sugar yield. Much of the other brix in sugarcane also causes operational difficulties during crystallization. Fiber in sugarcane, i.e., bagasse, can be utilized as biofuel in sugar mills.

The model inputs were defined as the actual technology options in the agricultural and industrial processes. The potential users of the model (the designers of combined sugar–ethanol production) are farmers, sugar mill industries, agricultural associations, and local governments. The model of the integrated sugarcane agricultural–industrial system included a cradle-to-grave system boundary, which is required for LCA. Design parameters for modeling were extracted from actual sugar mills.

An integrated model of agriculture and industry should be able to provide a new type of motivation for agricultural technology development. In conventional breeding, the objective function has been related to the quality of sugarcane, such as the purity of the sucrose in the cane. Nowadays, low agricultural quality does not always result in low quality of the final products. This is because the industrial conversion technology is well developed and desirable agricultural products are slightly changed by such development and social change, e.g., the increased value of biomass products. A mathematical model should be able to support a seamless attribution of such total objective functions to the target of agricultural technology development.

Modeling Approach

An overview of the proposed integrated model of combined raw Sugar–bioethaNol production from sugarcane (SugaNol model) is shown in Figure 3-2. The model has agricultural and industrial process modules. Both process modules convert scenario settings, represented as sets of process parameters, into process inventories including utility consumption, direct emissions, and products. In the agricultural process module, process parameters for the cultivation conditions, farm operation, and machine capacities are converted into process inventories as outputs. The data on the quality of sugarcane, which form the interconnection with the industrial process module, are transferred to the next module. The transport process is calculated as an intermediate process between the agricultural and industrial processes. In the industrial process module, process parameters for the manufacturing operations and machine capacities are provided, and the results of the agricultural process module are converted into process inventories.

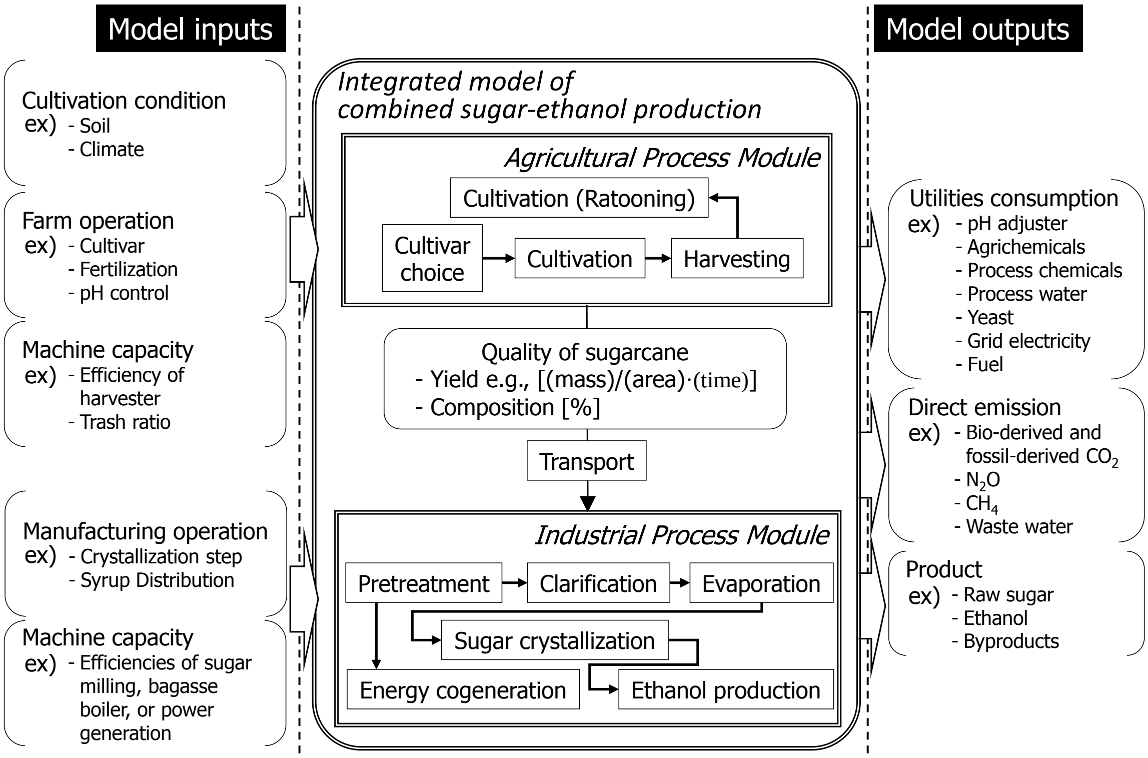


Figure 3-2 Overview of proposed integrated model of combined sugar–ethanol production from sugarcane.

Existing data tables and literature about agricultural processes was investigated. For example, the report published by KARC (2004) organized data about the individual characteristics of sugarcane cultivars and sugarcane cultivation such as quality of sugarcane with cultivation conditions. Such data are mainly classified for three cropping types (spring-planted, summer-planted, and ratoon crops) and several cultivation regions in Japan. The seedlings of spring-planted and summer-planted crops are planted in spring and summer, respectively. Spring-planted crops are harvested after a year from planting, whereas summer-planted ones are done after a year and a half from planting. Ratoon crops are grown from the buds on remaining after last-year harvesting. Because the period and way of cultivation vary depending on cropping types, it has a great impact on the yield and composition of sugarcane. Other publications (Okinawa Prefecture, 2006; Okinawa Prefecture, 2014; Kagoshima Prefecture, 2010) provided information on recommended farm operation for certain sugarcane-planting regions using recommended cultivars with the relationship between characteristics of sugarcane and farm operation, such as the amount of fertilizer, adjusted pH of soils, and irrigation frequency.

With regards to the industrial processes, operation records of actual sugar mills receiving cane-top-removed sugarcane and producing only raw sugar was scrutinized. Except for automation of process control by installing a distributed control system, or replacement of older unit operations with more developed ones, the main structure of the sugar mill process has not changed since about 1850

(Yoshizumi et al, 1986). However, the lack of change in the basic process structure has resulted in little systematized understanding of detail items in sugar mills. Through detailed investigation and monitoring, the data and knowledge required to construct process modules considering novel technology options in the agricultural and industrial processes were gathered.

In addition, empirical knowledge of sugarcane cultivation and sugar production was incorporated into the integrated modeling. Especially in the agricultural process, no effective mathematical models had been developed for analyzing the total performance of cultivation for different farm operations under different cultivation conditions. A great deal of experience has been accumulated as empirical knowledge but has not been expressed as data sufficiently. This is why a kind of heuristics of cultivation was gathered by listening to agricultural experts and converted into equations.

As a development environment, we utilized the Microsoft® Excel® spreadsheet application developed by the Microsoft Corporation. Visual Basic for Applications, an implementation of Microsoft's programming language, was also used for defining original functions.

3.2.3. Process Modeling of Sugarcane Farming and Sugar Milling and Ethanol Production Processes

Unit modeling

Figure 3-3 schematically shows the block flows considered in the developed model. The target process system for modeling was bounded and the units inside it were specified based on interviews with experts and on-site engineers, and the literature (Kikuchi et al., 2016b; Yamane, 1967; Rein, 2007) The boundary of the agricultural process module is from farm operations to harvesting and that of the industrial one is from cane cleaning to raw sugar and anhydrous ethanol production. Both the agricultural and industrial process modules consist of several stages. The agricultural process module has three stages: cultivar choice, cultivation, and harvesting. The yielded sugarcane is characterized through the three stages where the relations among the quality of sugarcane and parameters including cultivar conditions, farm operations, machine capacities, and internal variables are modularized. These modules are the integration of the regression models from the collected data and assumptions that a linear or quadratic relation among them is applicable, especially for unrevealed agricultural phenomena, and some constraints derived from the heuristics gathered for cultivation. The industrial process module has six stages: pretreatment, clarification, purification, sugar production, ethanol production, and energy cogeneration. The mass balance of all related components is quantified in every process unit. Industrial modules employ physical models that describe the phenomena as well as empirical formulas from the literature and regression models from the collected data.

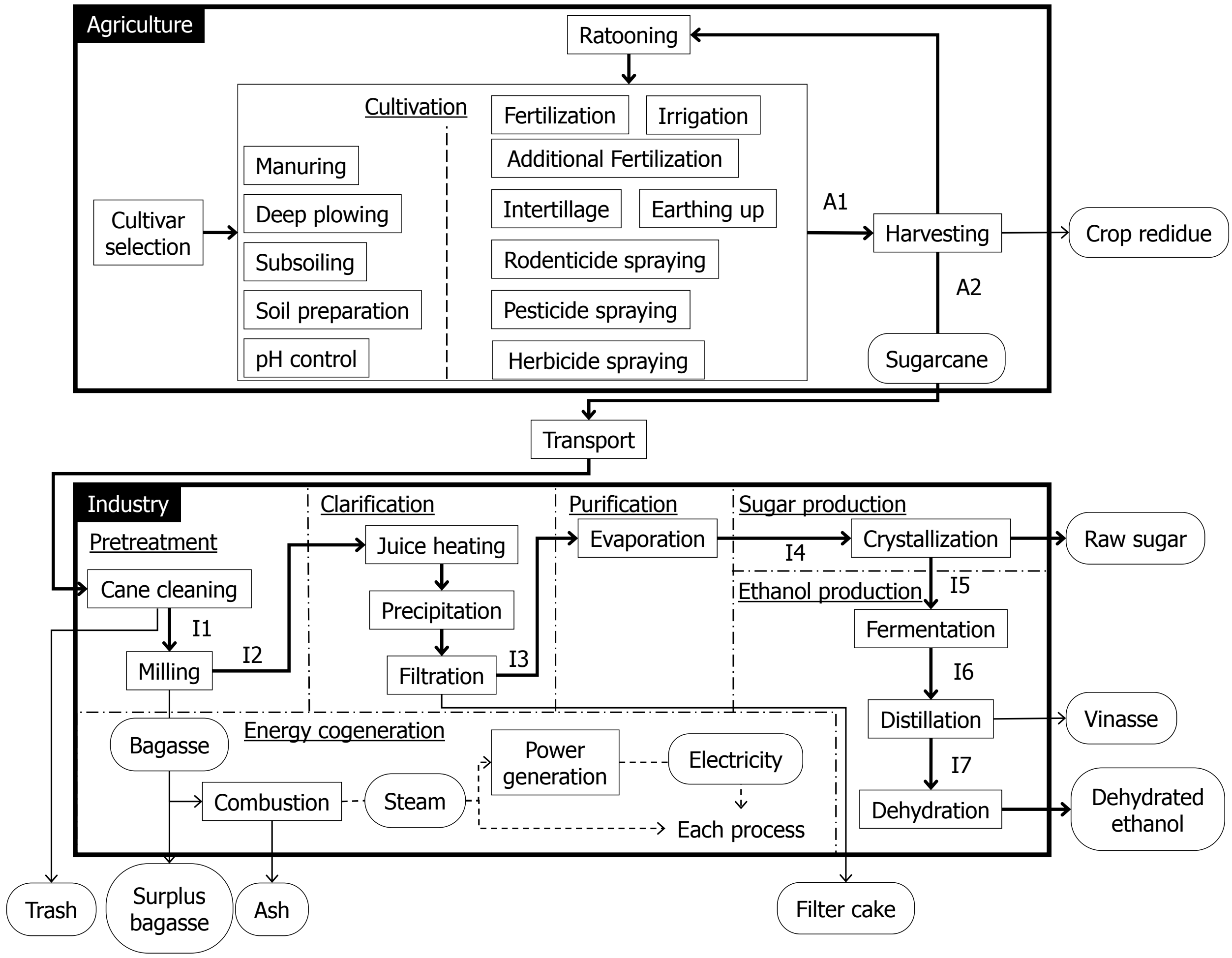


Figure 3-3 Process flows of materials and products in the process submodules.

Basic mathematical expressions

In the following, basic equations are expressed using variables and parameters defined in the "Notation" section. The modeled sugarcane consists of three parts: stem, cane top (the head part of the sugarcane), and leaf. In general, cane tops and leaves are regarded as inhibitors for sugar extraction and, therefore, most of them are removed together in cane burning or harvesting. Each of these three parts is composed of five components: sucrose, reducing sugars, other brix, fiber, and water. The streams in ethanol production may contain ethanol, CO_2, cell mass, and organic acids in addition to the above five components. The weights and proportions of all of the components always satisfy the following two equations:

$$F^i_{j(k)} = F_{j(k)} \cdot C^i_{j(k)}, \quad \forall i, j, k \tag{1}$$

$$\sum_i C^i_{j(k)} = 1, \quad \forall j, k \tag{2}$$

where $F^i_{j(k)}$ is the weight of component *i* in part *k* in stream *j*, $F_{j(k)}$ is the total weight of part *k* in stream *j*, and $C^i_{j(k)}$ is the proportion by weight of component *i* in part *k* in stream *j*. In addition to the above parameters, two indicators are introduced to quantify the quality of materials: brix concentration and sucrose purity. Brix is defined as the total content of dissolved solid substances and sucrose purity is defined as the ratio of sucrose to brix in the agricultural fields. These parameters can be described as:

$$C_{j(k)}^{\mathrm{bx}} = C_{j(k)}^{\mathrm{suc}} + C_{j(k)}^{\mathrm{red}} + C_{j(k)}^{\mathrm{obx}}, \quad \forall j, k \tag{3}$$

$$Pur_{j(k)} = \frac{C_{j(k)}^{\mathrm{suc}}}{C_{j(k)}^{\mathrm{bx}}}, \quad \forall j, k \tag{4}$$

<u>*Agricultural process module*</u>

Figure 3-3 also shows the procedures of sugarcane farming. Farmers decide cultivar and cropping type before the beginning of the farming period. For new-planted crops (i.e., spring-planted and summer-planted), preparation of the fields and planting are required, while for ratoon crops, a ratooning treatment is implemented instead. After planting or ratooning, additional fertilizers are applied twice accompanying intertillage and earthing up. Irrigation water and several kinds of chemicals, including pesticides and herbicides, are sprayed during the growing season.

In this model, the properties of the sugarcane, such as crop yield per FU and the composition, are determined as shown in the following two equations:

$$C0^{i} = f_{\mathrm{Sel}}^{i}(reg, cul, cro), \quad i = \mathrm{suc}, \mathrm{red}, \mathrm{bx}, \mathrm{fib} \tag{5}$$

$$F0 = ff_{\mathrm{Sel}}(reg, cul, cro) \tag{6}$$

where the $C0^{i}$ are the proportions of component *i*, which are soluble-weight-based for sucrose, reducing sugars, and brix, and total-weight-based for fiber in the cane without considering the effects of cultivation, and $F0$ is the stem weight of yielded sugarcane and also includes no effects of cultivation. f_{Sel}^{i} and ff_{Sel} are the growth indexes for component *i* and the stem weight, respectively, determined by three operational parameters, *reg*, *cul*, and *cro*. *reg* is the planted region such as Tanegashima or Tokunoshima, *cul* is the cultivar, and *cro* is the cropping type. The three major cropping types in Japan are spring-planted, summer-planted, and ratoon crops. Spring-planted crops are planted in spring and harvested in the next spring, while summer-planted ones are planted in summer and harvested in the spring of the second year of growth. The roots and the lower parts remain underground after harvesting and these parts can be grown as ratoon crops without soil preparation.

Table 3-2 shows the values of $F0$ and $C0^{i}$. NiF8 is the current mainstream cultivar in the southwestern islands of Japan for its high sucrose content. NiTn18 and KY01-2044 are unpopular cultivars that are recognized as high-yielding sugarcanes. They contain low sucrose and high fiber compared with NiF8. The statistical raw data from the agricultural experiment stations are for agricultural operations that are ideal for their growth. The standardized values when no farm operation is selected are shown in Table 3-2. These were specified from raw data (MAFF, Japan, 2014; KARC, 2004; KARC, 2013) and the modification procedures described below.

Table 3-2 Values of Parameters Related with Cultivar Choice Module

cul	NiF8		KF92-93		KY01-2044	
cro	Spring-planted	Ratoon	Spring-planted	Ratoon	Spring-planted	Ratoon
reg: Tanegashima						
$F0$	27.0	28.4	33.7	37.9	33.1	38.3
$C0^{sj}$	0.150	0.149	0.145	0.147	0.128	0.120
$C0^{rj}$	0.004	0.004	0.005	0.005	0.005	0.005
$C0^{bj}$	0.166	0.166	0.162	0.165	0.150	0.144
$C0^{fib}$	0.114	0.115	0.136	0.141	0.145	0.144
scr	5	5	1	1	1	1
reg: Tokunoshima						
$F0$	26.0	22.5	26.5	25.4	29.9	29.2
$C0^{sj}$	0.149	0.171	0.130	0.157	0.139	0.156
$C0^{rj}$	0.004	0.004	0.005	0.005	0.005	0.004
$C0^{bj}$	0.165	0.185	0.154	0.178	0.160	0.177
$C0^{fib}$	0.117	0.124	0.150	0.154	0.149	0.156
scr	5	5	1	1	1	1

Considering the effects of cultivation on the growth of the yielded sugarcane, the following equations for the modifications are applied:

$$F_{\mathrm{A1(stem)}} = \left(\prod_l ff_l\right) \cdot F0 \tag{7}$$

$$C^i_{\mathrm{A1(stem)}} = \left(1 - C^{\mathrm{fib}}_{\mathrm{A1(stem)}}\right) \cdot \left(\prod_l f^i_l\right) \cdot C0^i, \quad i = \mathrm{suc, red, bx} \tag{8}$$

$$C^{\mathrm{fib}}_{\mathrm{A1(stem)}} = \left(\prod_l f^{\mathrm{fib}}_l\right) \cdot C0^{\mathrm{fib}} \tag{9}$$

where f^i_l and ff_l are the growth indexes for component *i* and the weight of stem by cultivation method *l*, respectively, and are determined by the operational parameters.

ff_{pH} and f^i_{pH} are functions of the final pH of the soil (pH_{fin}) as follows:

$$ff_{\mathrm{pH}} = 1 + 0.0323(pH_{\mathrm{final}} - 6.5) \tag{10}$$

$$f^i_{\mathrm{pH}} = 1 + 0.0177(pH_{\mathrm{final}} - 6.5), \quad i = \mathrm{suc, red, obx} \tag{11}$$

$$f^{\mathrm{fib}}_{\mathrm{pH}} = 1 \tag{12}$$

These equations are regression models from reports (Okinawa Prefecture, 2006). pH_{fin} is determined by the initial pH (pH_{ini}) and the mean amount of pH adjusters applied (adj):

$$pH_{\mathrm{final}} = pH_{\mathrm{initial}} + fph(soil) \cdot adj \tag{13}$$

where $fph(soil)$ is the pH adjusters required to increase soil pH by 1.0 and determined by the soil type as shown in Table 3-3, which was derived from estimations in the literature(Okinawa Prefecture, 2006; Kagoshima Prefecture, 2003), and the range of pH is:

$$4.3 \leq pH_{\text{initial}} \leq pH_{\text{final}} \leq 7.0. \tag{14}$$

Table 3-3 Soil Type and *fph*

soil	*fph*	Description
Jahgaru	0	Assumption (pH is inherently alkaline and no lime is considered necessary)
Shimajiri Mahji	3.27	Assumption (the same value as for Kunigami Mahaji, based on rough estimation)
Kunigami Mahji	3.27	Okinawa Prefecture. Sugarcane cultivation guideline
Andosol	8.25	Kagoshima Prefecture Agriculture Department 2003

Calcium carbonate is recognized as a standard pH adjuster for farmland. Magnesium lime, slaked lime, and fused phosphate also have pH-adjusting effects. adj explains the total effects of applied alkaline materials using the following equation:

$$adj = \sum_q \frac{alk_q}{fca_q} \tag{15}$$

where alk_q is the application amount of alkaline material q, and fca_q is a conversion factor for alkaline materials into calcium carbonate shown in Table 3-4 (Kagoshima Prefecture, 2003). This model prepares four types of soil: Jahgaru, Shimajiri Mahji, Kunigami Mahji, and Andosol. Jahgaru, which is widely distributed in Southern Okinawa Island, has high nutrient content and is usually alkaline. If the soil is Jahgaru in the model, no pH adjuster is required. Shimajiri Mahji and Kunigami Mahji exist mainly in Tokunoshima and the Amami Islands and are formed from limestone, slate, or granite, respectively. Andosol has a wide distribution in Tanegashima and contains much humus.

Table 3-4 Conversion Factors for Alkaline Materials into Calcium Carbonate

q	*fcaq*
Calcium carbonate	1
Magnesia lime	1
Slaked lime	0.8
Fused phosphate	1.3
Calcium silicate	1.5

f_{Frt}^{i} and ff_{Frt} are functions of frz_{N}, which is the amount of nitrogen fertilizer per FU:

$$f_{\mathrm{Frt,stem}}^{i} = 1 + 7.99 frz_{\mathrm{N}} \quad i = \mathrm{suc, red, bx} \tag{16}$$
$$f_{\mathrm{Frt,stem}}^{\mathrm{fib}} = 1 \tag{17}$$
$$ff_{\mathrm{Frt}} = 1 + 0.41 frz_{\mathrm{N}} \tag{18}$$

Although fertilization effects vary depending on the soil properties, such as components, nutrient content, and textures, we assumed that those effects are negligible and simply employed a single function for each indicator above. These functions are regression models obtained from the data for red–yellow soil (*Kunigami Mahji*).

ff_{Ir} is a function of ir, which is the average irrigation water amount per day during the appropriate season, and is described as follows:

$$ff_{\mathrm{Ir}} = 1 + 0.192 ir \tag{19}$$

This equation is also a regression model from cultivation data (Kagoshima Prefecture, 2010). The main irrigation season is from July to October and the total number of irrigation days is assumed to be 115, based on the literature.

There are some limitations on $F_{\mathrm{A1(stem)}}$, frz_{N}, and ir:

$$F_{\mathrm{A1(stem)}} \leq FM \tag{20}$$
$$f_{\mathrm{Frt,stem}}^{i} = 1 + 7.99 NM, \quad i = \mathrm{suc, red, bx} \ \forall frz_{\mathrm{N}} \geq NM \tag{21}$$
$$ff_{\mathrm{Ir}} = 1 + 0.192 IM, \ \forall ir \geq IM \tag{22}$$

where *FM*, *NM*, and *IM* are the maximum values of $F_{\mathrm{A1(stem)}}$, frz_{N}, and ir, respectively, and should be specified by heuristics. For Okinawa Island in Japan, e.g., FM can be set to 143×10^{3} $\mathrm{ha^{-1}\ year^{-1}}$ in reference to the champion profile of the sugarcane contest held on Okinawa in 2014 (Okinawa Prefectural Sugar Industry Development Association, 2016). In addition, if no irrigation water is applied, f_{pH}^{i}, f_{Frt}^{i}, ff_{Frt}, and ff_{pH} are reduced to one even if the soil pH is appropriately controlled or large amount of fertilizers are applied. In other words, it is not until irrigation is selected that the positive effects of the soil pH control and the fertilization application on the growth of sugarcane can emerge.

All stems are transported to sugar mills while some cane tops and leaves are removed through cane burning and harvesting. The weights of transported cane tops and leaves are

$$F_{A1(k)} = (1 - bur_k) \cdot hv_k(hw) \cdot tl_k \cdot F_{A1(\text{stem})}\ k = \text{top, leaf} \tag{23}$$

where tl_k is the ratio of part k to stem, as shown in Table 4; hw is the selected harvesting technique, i.e., hand or harvester; $hv_k(hw)$ is the harvesting ratio of part k by hw; and bur_k is the removal ratio of part k by cane burning. Table 3-5 also shows the compositions of cane top and leaves. These properties were derived from reports (MAFF, Japan, 2014; KARC, 2004; KARC, 2010; Kagoshima Prefecture, 2010) based on the assumption that their properties do not vary much depending on cultivar, cropping type, and cropping region.

Table 3-5 Weight Ratio to Stem and Compositions of Cane Tops and Leaves

	k	
	Top	leaf
tl_k	0.149	0.130
$C^{suc}_{A1,k}$	0.044	0.154
$C^{red}_{A1,k}$	0.006	0.007
$C^{obx}_{A1,k}$	0.036	0.026
$C^{water}_{A1,k}$	0.735	0.724
$C^{fib}_{A1,k}$	0.179	0.228

Cane burning is an option for saving labor for harvesting. If cane burning is selected, some proportion of cane tops and leaves are lost as greenhouse gases (GHG), such as CO_2, N_2O, and CH_4, before harvesting. The remainder is harvested by hand or harvester. The harvesting rate depends on the harvesting technique. The remainder becomes harvesting residue and is kept on the soil. The mass balances are:

$$F_{crr} = \sum_k (1 - bur_k) \cdot \left(1 - hv_k(hw)\right) \cdot F_{A1(k)},\ \ k = \text{top, leaf.} \tag{24}$$

The removal ratio of cane tops and leaves by burning and harvesting set in the model are shown in Table 3-6. We assumed burning does not reduce stems, but does reduce cane tops and leaves at some rate. The removal ratio varies by harvesting technique. Hand cutting can almost completely remove cane tops and leaves, whereas harvester cutting cannot. Based on this fact, the values in Table 3-6 were roughly estimated (Macedo et al., 2004).

Table 3-6 The Removal Ratio of Cane Tops and Leaves by the Operation of Burning and Two Harvesting Techniques

	k	
	Top	Leaf
bur_k	0.72	0.72
hv_k (hand)	1	1
hv_k (harvester)	0.7	0.7

<u>*Industrial process submodule.*</u>

Pretreatment. Pretreatment consists of two steps. The first step is cane cleaning, in which a cane stripper and a trommel remove cane tops and leaves as trash, as follows:

$$F^i_{\mathrm{I1}(k)} = (1 - tr_k) \cdot F^i_{\mathrm{A2}(k)},\ k = \mathrm{top, leaf} \tag{25}$$

$$F^i_{\mathrm{trs}} = \sum_k tr_k \cdot F^i_{\mathrm{A2}(k)},\ k = \mathrm{top, leaf} \tag{26}$$

$$tr_k = \frac{scr(cul)}{5},\ k = \mathrm{top, leaf} \tag{27}$$

where tr_k is the removal rate of part *k* in cane cleaning and $scr(cul)$ is an index that represents the ease of scraping cane tops and leaves according to five grades. $scr(cul)$ varies depending on the cultivar; each value is quoted from new cultivar reference reports (MAFF, Japan, 2014; KARC, 2004; KARC, 2013) and shown in Table 3-2. The next process is milling, in which all of the cleaned stems, with some unremoved cane tops and leaves, are crushed and converted into cane juice and bagasse by the milling machine with some added water, called maceration water. Fiber contributes to the loss of brix in milling (King et al., 1965; Chen and Chou, 1993), while it is common knowledge that increased maceration water improves brix extraction. Wienese (1990) considered that the ratio of maceration water to fiber has an effect on brix extraction and developed a model that describes the relationship. He also proposed the formula for sucrose extraction described below based on the difference in elution tendencies between sucrose and brix. Extraction rates of sucrose (ess) and brix (ebs) are determined by his model, and the mass balances are:

$$F^{\mathrm{suc}}_{\mathrm{bag}} = (1 - ess) \cdot F^{\mathrm{suc}}_{\mathrm{I1(stem)}} + (1 - ebt) \cdot \left(F^{\mathrm{suc}}_{\mathrm{I1(top)}} + F^{\mathrm{suc}}_{\mathrm{I1(leaf)}}\right) \tag{28}$$

$$F^i_{\mathrm{bag}} = \left((1 - ebs) \cdot F^{\mathrm{bx}}_{\mathrm{I1(stem)}} - F^{\mathrm{suc}}_{\mathrm{bag}}\right) \cdot \frac{F^i_{\mathrm{I1(stem)}}}{F^{\mathrm{red}}_{\mathrm{I1(stem)}} + F^{\mathrm{obx}}_{\mathrm{I1(stem)}}} + (1 - ebt) \cdot \left(F^i_{\mathrm{I1(top)}} + F^i_{\mathrm{I1(leaf)}}\right),$$

i = red, obx (29)

$$F^{\mathrm{fib}}_{\mathrm{bag}} = \sum_k F^{\mathrm{fib}}_{\mathrm{I1},(k)}. \tag{30}$$

where ebt is the brix extraction rate from cane tops and leaves by the roll mills (RM). The water content of bagasse is fixed at wc^{bag}. The cane juice is obtained from the cane and maceration water by subtracting bagasse:

$$F_{\text{I2}}^{i} = \sum_k F_{\text{I1}(k)}^{i} - F_{\text{bag}}^{i}, i = \text{suc, red, obx, fib} \tag{31}$$
$$F_{\text{I2}}^{\text{water}} = \sum_k F_{\text{I1}(k)}^{\text{water}} + mw \cdot \sum_k F_{\text{I1}(k)} - F_{\text{bag}}^{\text{water}} \tag{32}$$

where *mw* is the ratio of maceration water per $\sum_k F_{\text{I1}(k)}$.

Clarification. The cane juice obtained from milling is heated to facilitate precipitation, and then clarified by continuous precipitation using slaked lime ($Ca(OH)_2$) and other agents as precipitants. Other brix and fiber are mainly removed as sediments from the cane juice. Small amounts of sucrose and reducing sugars are also caught in the sediments. The sediments are separated from the cane juice to form clear juice and sludge, called filter cake, through an Oliver filter. The water content of the filter cake is fixed at wc^{cake} and the amounts of the other components are given by:

$$F_{\text{cake}}^{i} = fcr^{i} \cdot F_{\text{I2}}^{i}, \quad i = \text{suc, red} \tag{33}$$
$$F_{\text{cake}}^{\text{obx}} = fcr^{i} \cdot F_{\text{I2}}^{i} + la \cdot F_{\text{I2}}. \tag{34}$$

where fcr^{i} is the removal rate of component *i* from cane juice in the clarification process, and la is the rate of addition of lime, which is categorized into other brix here, with respect to the weight of cane juice. The composition of the clear juice is calculated by:

$$F_{\text{I3}}^{i} = F_{\text{I2}}^{i} - F_{\text{cake}}^{i}, \quad i = \text{suc, red, water} \tag{35}$$
$$F_{\text{I3}}^{\text{obx}} = F_{\text{I2}}^{\text{obx}} + la \cdot F_{\text{I2}} - F_{\text{cake}}^{\text{obx}} \tag{36}$$

Evaporation. The clear juice is evaporated until the brix concentration reaches the goal bxo through multiple-effect evaporators. In this way the mass balance of the water is:

$$F_{\text{I4}}^{\text{water}} = \frac{1-bxo}{bxo} F_{\text{I3}}^{\text{bx}} \tag{37}$$

The weights of the other components, such as sucrose, reducing sugars, and other brix, do not change here. The evaporated water is emitted as drainage.

Sugar production. In the crystallization process, syrup is converted into raw sugar, molasses, and vapor through at most three crystallization steps. Figure 3-4 shows the detailed process flow in the crystallization process. This flow was designed based on the “Three boiling system” generally adopted in Japan (Yamane, 1967). The syrup, first molasses, and second molasses are respectively divided and distributed to several different subprocesses. The distribution ratios are calculated by

$$F_{pp,pp'}^{i} = d_{pp,pp'} \cdot F_{pp'}^{i}, \ \ \forall i \tag{38}$$

where $F_{pp,pp'}^{i}$ is the flowrate from subprocess pp to pp' and $d_{pp,pp'}$ is the division ratio from subprocess pp to pp'. Syrup is distributed to at most five subprocesses: seed preparation, first crystallization, second crystallization, third seed making, and magma making. Magma is a semisolid mixture of sugar and syrup. Seed preparation is the operation of evaporating syrup in a crystallizer and gaining seed crystals, which are used later as nuclei for promoting sucrose crystallization. The seed crystals are divided into two, the first seed and the second seed, and distributed to the first and second crystallizations, respectively. In the *n*th crystallization, the drawn syrup or molasses is mixed with the *n*th seed as mother liquor, evaporated until the brix content reaches $bxo_{\text{mas}(i)}$, and converted into massecuite, which is a dense mass of sugar crystals mixed with mother liquor. Some water is generally added in advance before the second and third crystallizations to reduce false grains, which inhibit crystallization. For the second and third crystallizations, water is added until the brix concentration reaches bxo_{cry}. The *n*th massecuite contains the crystallized *n*th raw sugar and *n*th molasses, and the following mass balance is always satisfied:

$$F_{\text{mas}(n)}^{i} = F_{\text{mo-mas}(n)}^{i} + F_{\text{su-mas}(n)}^{i}, \ \ n = 1,2,3 \ \ \forall i \tag{39}$$
$$F_{\text{su-mas}(n)} = y_n \cdot F_{\text{mas}(n)}^{\text{bx}}, \ \ n = 1, 2, 3 \tag{40}$$

where y_n is the yield rate of raw sugar in the *n*th crystallization step and is determined by a model based on the equation suggested by Broadfoot et al. (2001), which described the crystal contents as a quadratic function of the massecuite purity as follows:

$$y_n = a_n \cdot {Pur_{\text{mas}(n)}}^2 + b_n \cdot Pur_{\text{mas}(n)} + c_n \tag{41}$$

where a_n, b_n, and c_n are coefficients of the quadratic function and are specific to each sugar mill. These values were prepared from regression analyses of actual data for every crystallization step, as shown in Table 3-7.

Table 3-7 Coefficients of Sugar Yield Equations in the Crystallization Process

n	a_n	b_n	c_n
1	-1.56	3.48	-1009
2	0.95	-0.51	0.48
3	0.83	-0.05	0.38

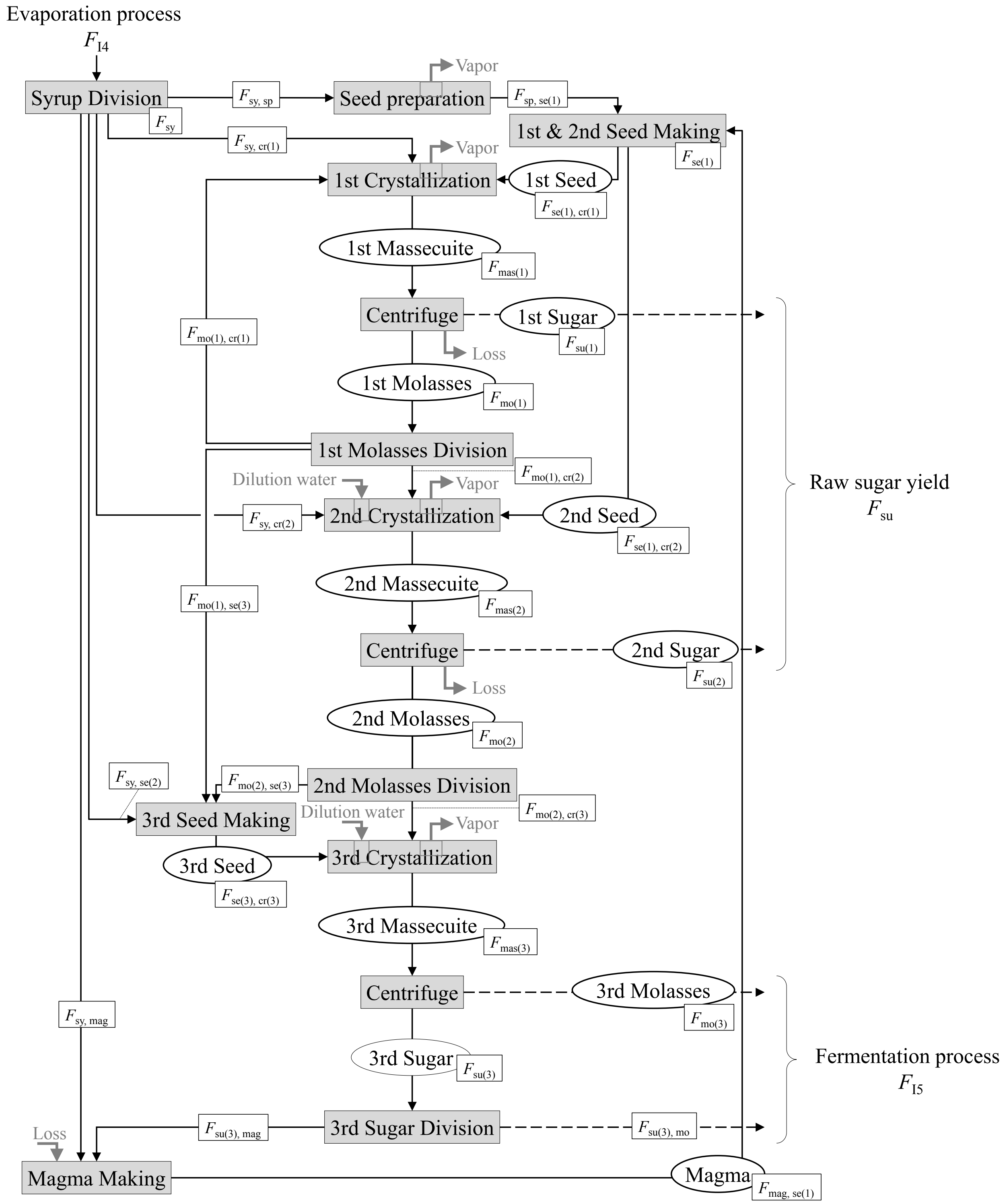


Figure 3-4 Process flows in the modeled crystallization process.

The raw sugar contains sucrose, reducing sugars, and other brix, and its sucrose purity is a fixed parameter for each crystallization step. The amount of reducing sugars and other brix is calculated by:

$$F^{i}_{\text{su-mas}(n)} = \frac{F^{i}_{\text{mas}(n)}}{F^{\text{red}}_{\text{mas}(n)} + F^{\text{obx}}_{\text{mas}(n)}} \cdot \left(F_{\text{su-mas}(n)} - F^{\text{suc}}_{\text{su-mas}(n)}\right), \quad n = 1, 2, 3 \quad i = \text{red}, \text{obx}. \quad (42)$$

The *n*th raw sugar in the *n*th massecuite is separated from the *n*th molasses with minimal loss by centrifugal separators. Allowing for some recovery loss, the amount of recovered raw sugar and molasses from the first and the second massecuites are calculated using:

$$F^{i}_{\text{su}(n)} = rc^{\text{su}} \cdot F^{i}_{\text{su-mas}(n)}, \quad n = 1, 2 \quad \forall i \quad (43)$$

$$F^{i}_{\text{mo}(n)} = rc^{\text{mo}} \cdot \left(F^{i}_{\text{mo-mas}(n)} + (1 - rc^{\text{su}}) \cdot F^{i}_{\text{su-mas}(n)}\right), \quad n = 1, 2 \quad \forall i \quad (44)$$

$$F^{i}_{\text{mas}(n),\text{mag}} = F^{i}_{\text{mas}(n)} - F^{i}_{\text{su}(n)} - F^{i}_{\text{mo}(n)}, \quad n = 1, 2 \quad \forall i \quad (45)$$

where rc^{q} is the recovery rate of q in the centrifugal separation. For the third massecuite, other equations are adopted considering the different phenomena: the third crystallization is not operated to achieve high recoveries because the material quality of the third massecuite is generally too low to crystallize and the raw sugar produced from it is not sold. Thus, the amount of the third raw sugar and the third molasses are calculated as follows:

$$F^{i}_{\text{su}(3)} = rc^{\text{su}} \cdot \left(F^{i}_{\text{su-mas}(3)} + mc \cdot F^{i}_{\text{mo-mas}(3)}\right), \quad \forall i \quad (46)$$

$$F^{i}_{\text{mo}(3)} = F^{i}_{\text{mas}(3)} - F^{i}_{\text{su}(3)}, \quad \forall i \quad (47)$$

where mc is the ratio of molasses attached to the crystal nuclei after centrifuging the third massecuite. The third raw sugar is recycled as magma, which is used for the first and the second seeds, after mixing with syrup. In this way, circular references among the equations in the crystallization process are created. An iterative calculation was adopted: The model was considered converged if the fluctuation range was less than 0.001 or after at most 100 iterations.

Ethanol production. Figure 3-5 shows the detailed process flow of the ethanol production unit, consisting of fermentation, distillation, and dehydration processes. The process design, process parameters and requirements for utilities assumed in this unit are mostly based on existing reports (Humbrid et al., 2011). The final molasses obtained from crystallization is fermented to ethanol using yeast. After fermentation, the ethanol is purified through distillation columns and a dehydration system to obtain a commercial ethanol product.

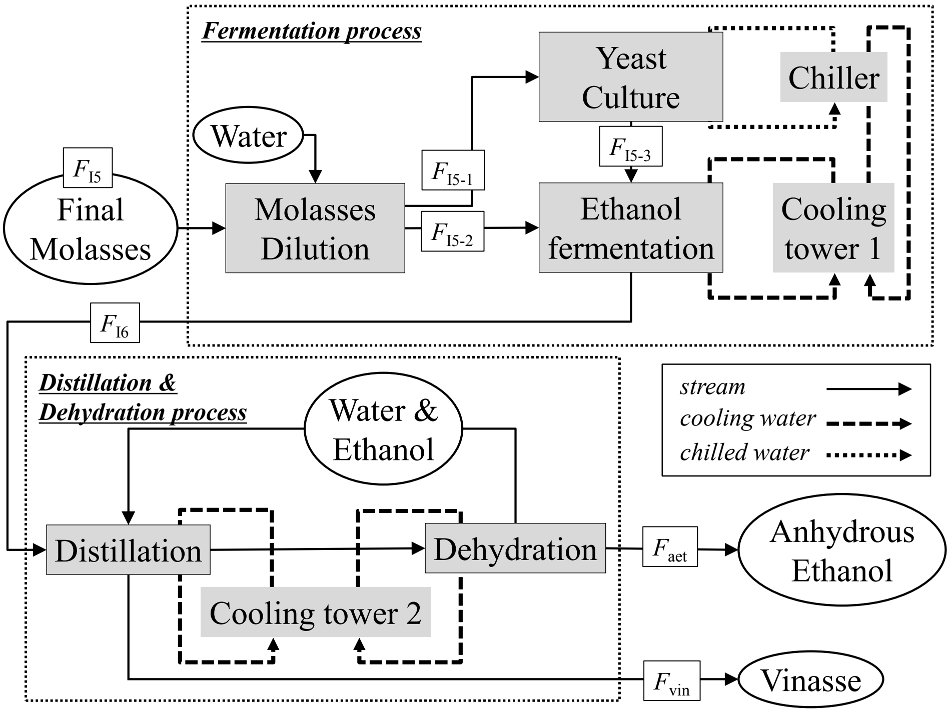


Figure 3-5 Process flows in the modeled fermentation and dehydration processes.

For effective fermentation, the molasses is first diluted to the appropriate mass concentration of sugars content (sco). Then 10% of the diluted molasses is split off to yeast culture tanks and used to culture yeast enough to conduct the subsequent fermentation. Inoculum from the yeast culture tanks and the remaining diluted molasses are fed to the ethanol fermenters, where ethanol, CO_2 and some by-products are produced after a batch operation. Table 3-8 lists the reactions and assumed conversions of yeast culture and ethanol fermentation; these were determined from existing reports (Humbrid et al., 2011). The temperature of the yeast culture tanks and the ethanol fermenters were controlled to 32 °C using chilled water and cooling water, respectively. The chilled water is supplied from a compression refrigerator, which requires electricity and cooling water. The cooling water duty is set equal to the load on the refrigerator. In both fermenters, sucrose is completely decomposed into reducing sugars by the enzymatic activity of *invertase* produced by the yeast and then partially converted into ethanol and CO_2 via sugar metabolisms, while the reducing sugars are directly converted into ethanol. Some organic acid and cell mass are also produced along with the main reactions.

The fermentation broth containing ethanol passes to distillation columns for refining to the targeted ethanol purity. The distillation columns remove CO_2 and most of the water including impurities as exhausted gas and a residue, called vinasse, from the broth, and thus a nearly azeotropic mixture of 92.5% ethanol and water is obtained. This ethanol is further refined using a zeolite dehydration system; the removed water, which contains unrecovered ethanol, returns to the distillation. As a result, 99.5% ethanol can be achieved by the additional investment of capital and utilities.

Table 3-8 Fermentation Reactions and Conversion Symbols

Reaction	Reactant	Conversion	
		Yeast Culture	Fermentation
$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$	$C_{12}H_{22}O_{11}$	$Xc_{\mathrm{suc}\rightarrow\mathrm{red}}$	$Xf_{\mathrm{suc}\rightarrow\mathrm{red}}$
$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$	$C_6H_{12}O_6$	$Xc_{\mathrm{red}\rightarrow\mathrm{etoh}}$	$Xf_{\mathrm{red}\rightarrow\mathrm{etoh}}$
$C_6H_{12}O_6 \rightarrow$ Cell mass	$C_6H_{12}O_6$	$Xc_{\mathrm{red}\rightarrow\mathrm{cell}}$	$Xf_{\mathrm{red}\rightarrow\mathrm{cell}}$
$C_6H_{12}O_6 \rightarrow$ Organic acid	$C_6H_{12}O_6$	$Xc_{\mathrm{red}\rightarrow\mathrm{org}}$	$Xf_{\mathrm{red}\rightarrow\mathrm{org}}$

Energy production. The bagasse produced in the milling process can be used as fuel to provide each process with steam and electricity. The energy balance in the modeled factory follows the research on sugar mills in Tanegashima (Kikuchi et al., 2016b). The bagasse is burned to generate high-pressure steam (HPS) in the bagasse boiler. This steam is transferred to a high-pressure steam header (HPSH). The total demand of bagasse (bd) is:

$$bd = \frac{hd}{\alpha(1-\delta_{\mathrm{HPSH}})H_{\mathrm{bag}}} \tag{48}$$

where hd is the energy demand of HPS, α is the combustion efficiency, δ_{HPSH} is the heat loss rate from the HPSH, and H_{bag} is the lower heating value (LHV) of bagasse. Based on the composition of the modeled bagasse, the standard enthalpy of combustion, H_{bag} can be calculated as follows (Hugot, 1960):

$$H_{bag} = 19.2F_{\mathrm{bag}}^{\mathrm{fib}} + 16.5F_{\mathrm{bag}}^{\mathrm{suc}} + 15.7F_{\mathrm{bag}}^{\mathrm{red}} - 2.51\{0.585F_{\mathrm{bag}} \cdot (1 - C_{\mathrm{bag}}^{\mathrm{water}}) + F_{\mathrm{bag}}^{\mathrm{water}}\}. \tag{49}$$

If bd is larger than F_{bag}, then the shortage is made up with fuel oil A in the equivalent energy amount. After adjusting the pressure and temperature at the HPSH, HPS is divided into three streams, RM, power-conversion turbine (PCT), and pressure-reducing valves (PRV), as necessary. The energy demand of HPS (hd) is given by:

$$hd = hd_{\mathrm{RM}} + hd_{\mathrm{PCT}} + hd_{\mathrm{PRV}} \tag{50}$$

where hd_m is the energy demand of HPS for machine m. hd_{RM} and hd_{PCT} are:

$$hd_m = \frac{W_m}{\eta_m} \quad m = \mathrm{RM, PCT} \tag{51}$$

where W_m is the work of machine m and η_m is the work efficiency of machine m. W_{RM} is proportional to the weight of the generated bagasse and W_{PCT} is calculated as follows:

$$W_{\mathrm{PCT}} = \frac{\sum_m ed_m}{3.6} \tag{52}$$

where ed_m is the electricity demand of machine m. The cascaded steam from the RM and the PCT can be used as low-pressure steam (LPS) in other equipment after going through the low-pressure steam header (LPSH). The available energy of the cascaded steam is:

$$lcas = (1 - \delta_{\mathrm{LPSH}})\left(\frac{(1-\eta_{\mathrm{RM}})hd_{\mathrm{RM}}}{\eta_{\mathrm{RM}}} + \frac{(1-\eta_{\mathrm{PCT}}-\delta_{\mathrm{PCT}})hd_{\mathrm{PCT}}}{\eta_{\mathrm{PCT}}}\right) \tag{53}$$

where δ_m is the energy loss rate of machine m. The energy demand of LPS (ld) is calculated by

$$ld = \sum_{m\in m3,m4m5} ld_m \tag{54}$$

where ld_m is the demand for LPS of machine m. If $lcas$ is larger than ld, then the demand for LPS is satisfied and the surplus LPS is emitted; otherwise, additional HPS is produced and decompressed to LPS by a PRV. In the latter case, the energy demand of additional HPS is:

$$hd_{\mathrm{PRV}} = \frac{ld-lcas}{1-\delta_{\mathrm{DC}}} \tag{55}$$

In this case, no surplus LPS is generated, while some of the energy is lost at the PRV as pressure reduction. From the usage of LPS in multiple-effect evaporators and crystallizers, heat is lost as a drain of exhausted steam.

Integration of the agricultural and industrial modules

The mathematical model developed above enables the seamless analysis of the combined agricultural and industrial processes to estimate the final products, raw sugar and anhydrous ethanol, as well as the analysis of industrial to agricultural processes to specify the most important characteristics on cultivar breeding. In the agricultural processes, the components and weight of the stems of the harvested sugarcane are subject to the selection of cultivar, agricultural operations, and cultivating environment. These properties affect the performance of the industrial processes. In this model, the components and the weight of sugarcane are determined by the agricultural inputs, including the agricultural operations and the environmental parameters. The yields of raw sugar and anhydrous ethanol are calculated from the agricultural output, which is also the industrial input, by analyzing the mass balance of the industrial processes.

3.2.4. Visualization of System Performance

Two case studies were undertaken to demonstrate the potential of the model.

Case Study A:

Case settings. Utilizing the process model, 1st molasses utilization network was analyzed to explain the relationship among the operational parameters and the process performances on a simulation basis.

The indicator about the pan-stage scheduling can be obtained by defining a crystallization pan load (CPL) as Eq.(56):

$$\mathrm{CPL} = \frac{F^{\mathrm{bx}}_{\mathrm{mas}(1)} + F^{\mathrm{bx}}_{\mathrm{mas}(2)} + F^{\mathrm{bx}}_{\mathrm{mas}(3)}}{F^{\mathrm{bx}}_{\mathrm{sy}}} \tag{56}$$

where $F^{\mathrm{bx}}_{\mathrm{mas}(n)}$ and $F^{\mathrm{bx}}_{\mathrm{sy}}$ are the weight of brix in the *n*th massecuite and in the syrup, respectively. In general, CPL is between 165% and 190% (Yamane, 1967). The high value of CPL indicates a large amount of the recycled molasses and, hence, tight scheduling.

The purity of syrup was chosen as 90% and 80% for the cases of the high and the low quality of syrup, respectively. The brix content was fixed at 60%. For simplification, no syrup was used for 2nd crystallization and graining. The seed crystals were boiled with mother liquor in four times the weight of the crystals. 3rd sugar was mixed with syrup in one third the weight of 3rd sugar. The division ratio of 1st molasses to graining and 1st crystallization was selected as a manipulated variable as shown in Table 3-9 to seek alternatives. The fixation of these parameter determines other division ratios of syrup and 1st molasses uniquely because of the freedom degree of design bound by the total mass balance in the three boiling system. The ratio of added water to the total weight of seed crystals and mother liquor in 1st, 2nd, and 3rd crystallization were set as 0.03 t/t-feed, 0.51 t/t-feed, and 0.51 t/t-feed, respectively. The final brix content of massecuite in each crystallization was 94%.

Results. Figure 3-6 shows the simulation result of 1st molasses division ratio and the total sugar yield. For both high and low purity cases, Case 2 displays the best sugar yield. Dividing 1st molasses to 1st crystallization stands for increasing 1st massecuite, degrading the purity of 1st massecuite, and reducing 2nd massecuite. The total yield enhancement brought by recycling 1st molasses outperforms its negative effects such as depressing the yielding rate of 1st sugar and the yield of 2nd sugar. If 1st molasses is used for graining as shown in Case 4-H and 4-L, the smallest total sugar yield is obtained among the four cases. Dividing 1st molasses to graining means that some 1st molasses skip 2nd crystallization and go directly to 3rd crystallization where it is easy for components including sucrose to leach out from the system due to the low yield of 3rd sugar. Comparing between high and low quality cases, the latter shows a larger gap of the yield between the maximum and the minimum cases. As the purity of syrup gets worse, the operators should be more careful about 1st molasses utilization networks.

Figure 3-7 shows the relationships among steam consumption, electricity consumption and CPL. It indicates that the purity of syrup significantly affects steam and electricity consumption considering the two large clusters of the plots. CPL is also greatly affected by the purity. For example, CPL of Case 2-L is 1.25 times as large as that of Case 2-H. The 1st molasses division ratio also has impacts on all the performances. With regard to high-purity cases, all four cases are on a Pareto curve. However, Case 1-L deviates from a Pareto curve in low-purity cases: its performances except for a sugar yield are inferior to those in Case 4-L. Operators have to judge the priority among the yield, scheduling of crystallization pans and energy consumption depending on cases.

Table 3-9 Case setting and case study results

		High purity				Low purity			
	Unit	Case 1-H	Case 2-H	Case 3-H	Case 4-H	Case 1-L	Case 2-L	Case 3-L	Case 4-L
Case setting									
Purity of syrup	%	90.0	90.0	90.0	90.0	80.0	80.0	80.0	80.0
1st molasses going to:									
1st crystallization	%	0	40	20	0	0	40	20	0
Graining	%	0	0	20	40	0	0	20	40
Results									
Syrup going to:									
1st and 2nd seed preparation	%	5.8	6.7	5.8	5.4	6.2	7.5	6.3	5.6
1st crystallization	%	92.7	92.1	92.2	91.8	91.2	90.2	90.7	90.6
Magma mixing	%	1.5	1.2	2.0	2.8	2.5	2.3	3.1	3.7
1st and 2nd seed going to:									
1st crystallization	%	85.5	90.4	92.1	91.5	76.8	83.3	84.6	84.6
2nd crystallization	%	14.5	9.6	7.9	8.5	23.2	16.7	15.4	15.4
Purity of 3rd molasses	%	30.0	26.3	34.4	38.7	26.4	24.1	29.3	32.2
CPL	%	173	206	177	167	212	258	217	199
Steam consumption	GJ	216	206	212	225	293	285	285	292
Electricity consumption	MWh	2.40	2.82	2.45	2.32	2.91	3.52	2.98	2.74

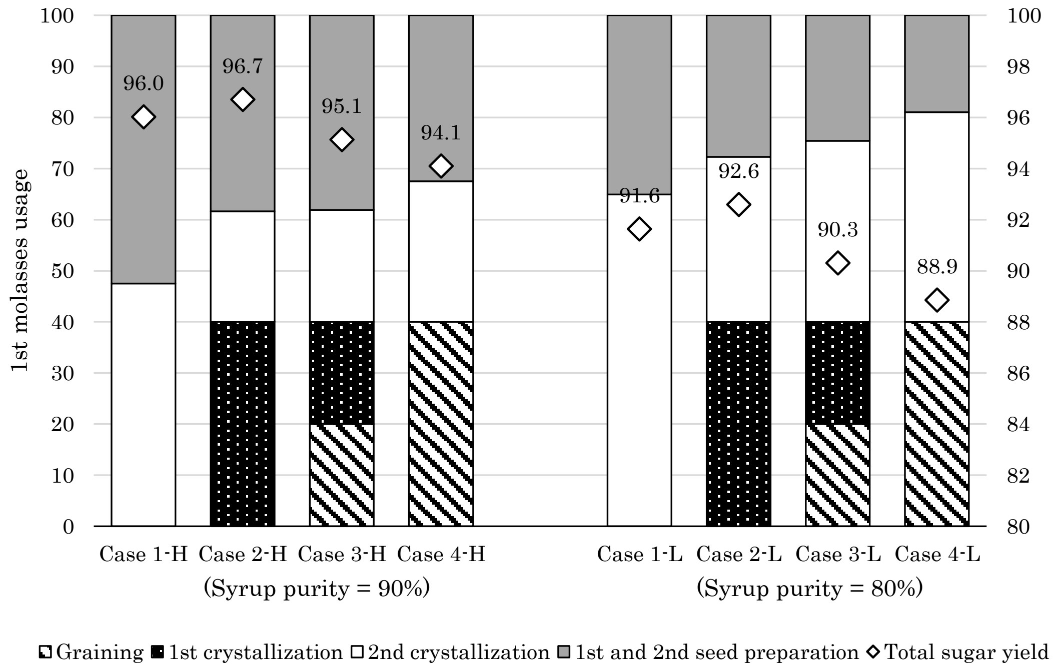


Figure 3-6 Distribution ratio of 1st molasses and total sugar yield.

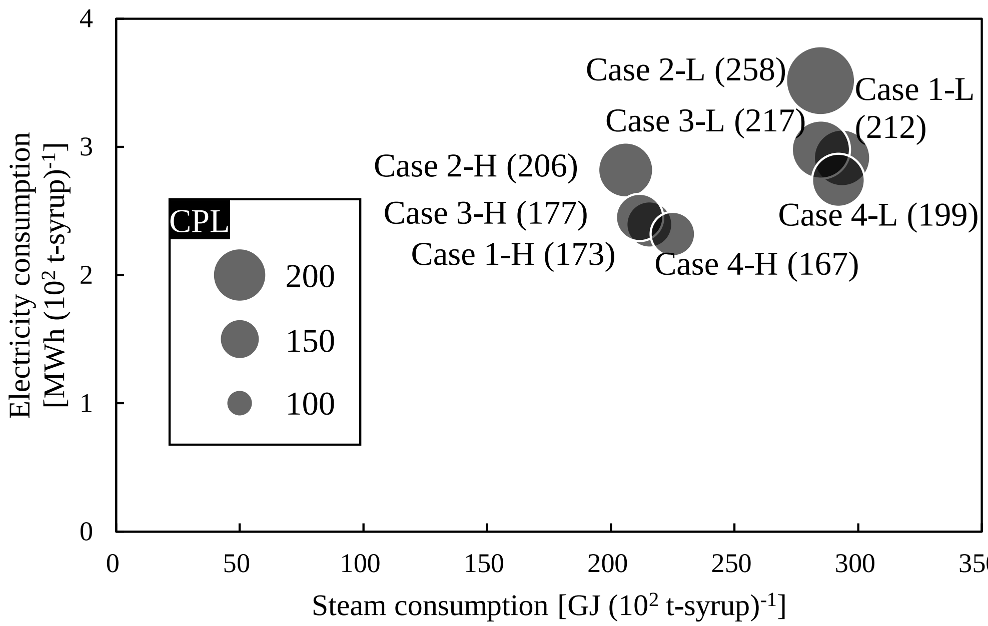


Figure 3-7 Relationships among steam consumption, electricity consumption and CPL. The size of circles is in proportion to CPL.

Case Study B:

This case study is undertaken for the redesign of combined sugar and bioethanol production considering both agricultural and industrial options. The spatial boundary was one hectare of sugarcane farmland and one factory coproducing raw sugar and anhydrous ethanol. The temporal FU is one year. The sugarcane cultivar on the agricultural side and maceration water and number of crystallizations on the industrial side were the variable options. As indicators of the process performance, raw sugar and anhydrous ethanol production, energy balance in the factory, economic revenues for both sides, cradle-to-gate LC-GHG emission, and the material flow of nitrogen-phosphorus-potassium (NPK) within the system were calculated from the resulting process inventory.

Assumptions. Table 3-10 shows the representative input parameters and restrictions for our case study. These values were determined from actual mill data and reports (Okinawa Prefecture, 2006; Okinawa Prefecture, 2014; Kagoshima Prefecture Sugar Industry Association, 2010; Okinawa Prefectual Sugar Industry Association, 2016). Other agricultural input materials to the farmland and the fuel demand of the agricultural equipment are listed in Tables A1 and A2 (Macedo et al., 2004; Shinzato, 2015; Kagoshima Prefecture, 2016; MLIT, Japan, 2014), respectively. The cropping type is spring-planted on half of the area and ratoon crops on the other half. The soil pH is adjusted to 6.0 by liming. The crops are not burned. They are harvested by harvesters and transported to the factory located 15 km from the farmland by 4-ton trucks. Cropping residues remain in the field. A cane stripper and a trommel are installed in the factory. The molasses is converted into dilute ethanol by *Zymomonas mobilis*, a Gram-negative bacterium that possesses desirable characteristics for sugar conversions, followed by purification to 99.5% anhydrous ethanol for gasoline substitution. All of the electricity demand is covered by the cogeneration system in the factory. Bagasse is used as fuel in preference to fuel oil A. Trash and surplus bagasse, if generated, are used as replacement fuels for fuel oil A in another combustion facility located 30 km from the factory. Bagasse ash, filter cake, and vinasse are returned to the farmland as nutrients, which allows a reduction in chemical fertilizers (Lisboa et al., 2011). These are transported by 4-ton trucks. All of the products are eventually decomposed and their carbon content is emitted into the air as CO_2 regardless of the path. Other process parameters of the industrial process in this case study are listed in TableA 3 (Kikuchi et al., 2016b; Basso et al., 2008; Yamane, 1967; Rein, 2007; Humbird et al., 2011; Hugot, 1960; Yanagida et al., 2010).

The income per farmland area per year for the farmers (IFR) was used as economic evaluation for the agricultural side. The expenses for sugarcane production derive from agricultural requirements and labor rates, although these are completely the same for all the cases studied. For economic evaluation, we can calculate the average expenses of inputs and labor over ten years from statistics (MAFF, Japan, 2015a) as 6.89×10^5 JPY ha^{-1} and 8.12×10^5 JPY ha^{-1}, respectively. Farmers' gain comes from the yielded crops, and their prices were determined by the current Japanese policy as the following equations (MAFF, Japan, 2007):

Table 3-10 Input Parameters and Restrictions for the Case Study

Symbol	Unit	Quantity
cro (50% area)		Spring-planted
cro (50% area)		Ratoon
reg		Tanegashima
$soil$		Andosol
pH_{initial}		5.5
pH_{final}		6
frz_{N}	10^3 kg ha^{-1} year^{-1}	0.16
frz_{P}	10^3 kg ha^{-1} year^{-1}	0.12
frz_{K}	10^3 kg ha^{-1} year^{-1}	0.15
ir	mm day^{-1}	1
hw		harvester
FM	10^3 kg ha^{-1} year^{-1}	143
NM	10^3 kg ha^{-1} year^{-1}	0.4
IM	mm day^{-1}	2.5

$$\text{IFR} = (PM + PS) \cdot F_{\text{A1(cane)}} \tag{57}$$

where PM is the market price of sugarcane per cane weight and PS is the subsidy paid to sugarcane farmers per cane weight. According to the Japanese policy, these two parameters are calculated as follows:

$$PM = RS \cdot DF \cdot YM \cdot CS, \tag{58}$$

$$PS = \begin{cases} PS0 + 1000(CS1 - CS), & CS \leq CS1 \\ PS0, & CS1 < CS \leq CS2 \\ PS0 + 1000(CS - CS2), & CS2 < CS \end{cases} \tag{59}$$

where RS is the resale price of raw sugar per unit weight in the last second quarter, DF is a distribution ratio assigned to farmers' contributions, YM is the standard yield in sugar mills, CS is the estimated sucrose composition in the stems of the yielded cane, $PS0$ is the standard subsidy paid to sugarcane farmers per cane weight, and $CS1$ and $CS2$ are the lower and upper ends, respectively, of the protection range of sucrose composition, over which the subsidy is constant and independent of the sugarcane quality. In reality, the sucrose composition of the sampled stem of the yielded cane is measured as CS by a near-infrared (NIR) spectrometer. In this study, we assume that the NIR spectrometer can accurately measure the sucrose component of sugarcane and CS is equal to

$C^{\mathrm{Bx}}_{\mathrm{A1(stem)}}$ in the model. The parameters used in Eqs (58) and (59) are listed in Table 3-11 based on policies in 2015 (MAFF, 2007; ALIC, 2016; MAFF, 2016). This case study utilized the equations shown above and IFR was evaluated as an agricultural economic indicator for each case.

On the industrial side, the income per farmland area per year for the factory (IFC) was accounted for. The factory purchases sugarcane paying PM to sugarcane farmers and makes profits from raw sugar and anhydrous ethanol sales as well as receiving credits from by-products. The market price of raw sugar is the same as the resale price, which is 84.2 JPY kg^{-1}. The price of anhydrous ethanol per MJ was assumed to be equal to gasoline, i.e., 67.2 JPY L^{-1}. The surplus bagasse and trash could be sold at 1.53 JPY MJ^{-1} based on the price of fuel oil A. Bagasse ash, filter cake and vinasse could be sold at the price of fertilizers they replace on a nitrogen, phosphorous and potassium content basis. The expenses derived from the input materials, transport and seasonal labor were subtracted from the profits. The required quantities and unit prices of input materials are shown in TableA 4 (MAFF Japan, 2015b; ALIC, 2016; ANRE, Japan, 2016b; The Chemical Daily, 2015; Okinawa Prefectual Enterprise Bureau, 2016; MLIT, Japan, 2008). Some of the materials are not treated as components in the model, but are reflected in the economics. The labor cost was set at 1.22×10^4 JPY $person^{-1}$ day^{-1}, which is 1.5 times the average income of citizens in 2012 in Nakatane Town (Nakatane Town, 2014) where the real sugar mill is located, considering insurance fees paid by the employers. The number of seasonal workers in the factory was set as 59 based on the actual conditions in the mill. The number of operation days was estimated as the quotient obtained by dividing the amount of processed sugarcane (F_{A1}) by the processing capacity, which was set as 1500×10^3 kg day^{-1}, also referring to the real mill.

Table 3-11 Parameters Related to Economic Evaluation

	Unit	Value
RS	JPY $(10^3\ kg)^{-1}$	84228
DF		0.48
YM		0.86
PS0	JPY $(10^3\ kg)^{-1}$	16420
CS1	%	13.1
CS2	%	14.3

The total GHG emissions were calculated based on the LCA, in which both emissions and absorptions associated with the life cycle of sugarcane were evaluated. The life cycle can be divided into the following stages: direct and indirect emissions in agricultural and industrial processes, absorption by sugarcane during the growing season, consumption, and decomposition of industrial products and by-products, and substitutions of products and by-products. The relevant GHGs in this study are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). All these gases were evaluated by multiplying global warming potentials (IPCC, 2007; 1 kg CO_2:1 kg CO_{2eq}, 1 kg N_2O:310

kg CO_{2eq}, 1 kg CH_4:21 kg CO_{2eq}). The emissions were calculated from the process inventories output from the model, multiplied by the emission factors derived from the LCA database of JLCA (2013), the Ecoinvent Database (2016), and IDEA (JEMAI, 2012), as well as the report by Kobayashi et al. (2006) and the Petroleum Energy Center (2000). The conditions of background processes follow these references. The factors are shown in Tables A5 and A6. As for the consumption of products and decomposition of by-products, some CO_2 is simply calculated on a carbon-composition basis under the assumption that all carbon is converted into CO_2 in the long term. The carbon content for each component is shown in TableA 7. The carbon content of sucrose, reducing sugars, and ethanol follow their molecular compositions. Other brix is considered a carbon-free component in the model. The carbon contents of cell mass and organic acids are made the same as that of reducing sugars based on the assumptions in the fermentation process. Sugarcane fiber consists of cellulose, hemicellulose, and lignin and its carbon content is determined by their composition and the carbon content of the three components shown in TableA 8 (Ouensanga, 1989; Landell et al., 2013).

Agricultural direct GHG emissions are derived from driving agricultural equipment, plowing soil during preparation of the field for new plantings, and the decomposition of applied input materials and cropping residue over the long term. All of the equipment used in this case study consumes diesel oil as fuel, as shown in TableA 2. On the one hand, deep plowing converts carbon in the soil existing from the beginning of the farm operations into GHGs. Input materials such as lime, manure, and nitrogen fertilizer also emit GHGs after their application. The cropping residue is assumed to be put on the farmland in this case study and the carbon content will be returned to the air as CO_2 after decomposition. On the other hand, the direct emissions from industrial sites are from the combustion of bagasse and/or fuel oil A and fermentation. The model output gives bagasse consumption and its carbon content as well as fuel oil A consumption if it is used; these enable us to calculate GHG emissions. CO_2 emission from yeast culture tanks and ethanol fermenters are direct outputs from the model. The emissions from the background processes, such as manufacturing and transporting input materials for agricultural and industrial processes, are accounted for as indirect emissions for each process.

Absorption of CO_2 during the sugarcane-growing season was regarded as a negative emission based on the assumption that all of the carbon in the sugarcane body is derived from atmospheric CO_2. It is also assumed that raw sugar and anhydrous ethanol are finally consumed and all of their carbon content will be converted into CO_2. Furthermore, the substitution of some materials (i.e., gasoline by anhydrous ethanol; fuel oil A by surplus bagasse; and nitrous, phosphorous, and potassium chemical fertilizers by bagasse ash, filter cake, and vinasse) were also considered. In other words, the emissions associated with manufacturing, transporting, and consuming those substituted materials were subtracted from the total GHG emissions. The substituted amount is given by equivalent combustion energy or nutrient content basis using the data shown in Tables A2 and A9 (Rein, 2007; Dee et al., 2002; Lisboa et al., 2011).

Results. A summary of the case study is shown in Table 3-12. In this table, the raw sugar production from the model and the sugarcane sugar-yield-related marker (SYM) calculated by the commercial cane sugar (CCS) formula (Yamane, 1967), which is the indicator traditionally utilized for deciding the value of crops in some countries, are also listed (see also the Discussion). In the CCS formula, we calculated SYM as the following equation:

$$\mathrm{SYM} = F_{\mathrm{A2(stem)}} \cdot \left(\frac{3}{2} Pur_{\mathrm{A2(stem)}} \cdot \left(1 - \frac{F^{\mathrm{fib}}_{\mathrm{A2(stem)}} + 5}{100} \right) - \frac{F^{\mathrm{bx}}_{\mathrm{A2(stem)}}}{2} \cdot \left(1 - \frac{F^{\mathrm{fib}}_{\mathrm{A2(stem)}} + 3}{100} \right) \right) \quad (60)$$

Table 3-12 Summary of the Case Study Results

		Cases												
	Unit	Base	1a	1b	1c	1d	2a	2b	2c	2d	3a	3b	3c	3d
Input parameters														
Cultivar (*cul*)			NiF8				NiTn18				KY01-2044			
Maceration water ratio (*mw*)	kg (kg-cane)$^{-1}$	0.2	0.2	0.2	0.2	0.5	0.2	0.2	0.2	0.5	0.2	0.2	0.2	0.5
Crystallization step (*n*)		3	1	2	3	3	1	2	3	3	1	2	3	3
Results														
Raw sugar	10^3 kg ha^{-1} year^{-1}	10.0	8.5	9.6	10.0	10.3	10.0	11.4	11.9	12.4	8.0	9.2	9.7	10.1
Raw sugar (SYM)	10^3 kg ha^{-1} year^{-1}	9.4	9.4	9.4	9.4	9.4	11.1	11.1	11.1	11.1	8.8	8.8	8.8	8.8
Anhydrous ethanol	kL ha^{-1} year^{-1}	0.0	1.75	1.04	0.79	0.91	2.40	1.52	1.19	1.37	2.27	1.48	1.18	1.33
IFR	10^6 JPY ha^{-1} year^{-1}	1.7	1.72	1.72	1.72	1.72	2.18	2.18	2.18	2.18	1.94	1.94	1.94	1.94
IFC	10^6 JPY ha^{-1} year^{-1}	0.4	0.35	0.40	0.42	0.43	0.44	0.50	0.53	0.57	0.35	0.41	0.44	0.47
Total GHG emission	10^3 kg ha^{-1} year^{-1}	1.9	-0.82	0.27	0.66	1.65	-4.07	-2.72	-2.20	-2.27	-4.27	-3.06	-2.59	-2.69

Figure 3-8a shows the results for the production balance of raw sugar and anhydrous ethanol. It shows that more raw sugar is obtained for all three cultivars with less anhydrous ethanol as more crystallization steps are used. This is because the summation of sucrose and reducing sugars is constant for a given cultivar. The amount of raw sugar crystallized in the first, second, and third steps decreased in that order, which matches the actual results in sugar mills (Ohara et al., 2009; Yamane, 1967). This is because the sucrose content is decreased by each crystallization, which reduces the recovery ratio of sucrose from massecuite to raw sugar. These characteristics of crystallization are independent of the cultivar while the amounts of products differ greatly among them. We observed from the comparison between NiF8 and NiTn18 that the total amount of raw sugar gained from NiF8 through three crystallizations can be gained from one crystallization of NiTn18. Although NiTn18 contains less sucrose than NiF8, more sugarcane can be obtained per unit area from NiTn18 than from NiF8. These rankings, however, may change for different cropping areas. Figure 3-8b shows that the productivity of NiTn18 is less than that of NiF8 in Tokunoshima. The productivity of KY01-2044, on the other hand, is higher than the others, while it has lower results in Tanegashima. We believe that this is a result of the compatibility between a cultivar and the cultivation environment.

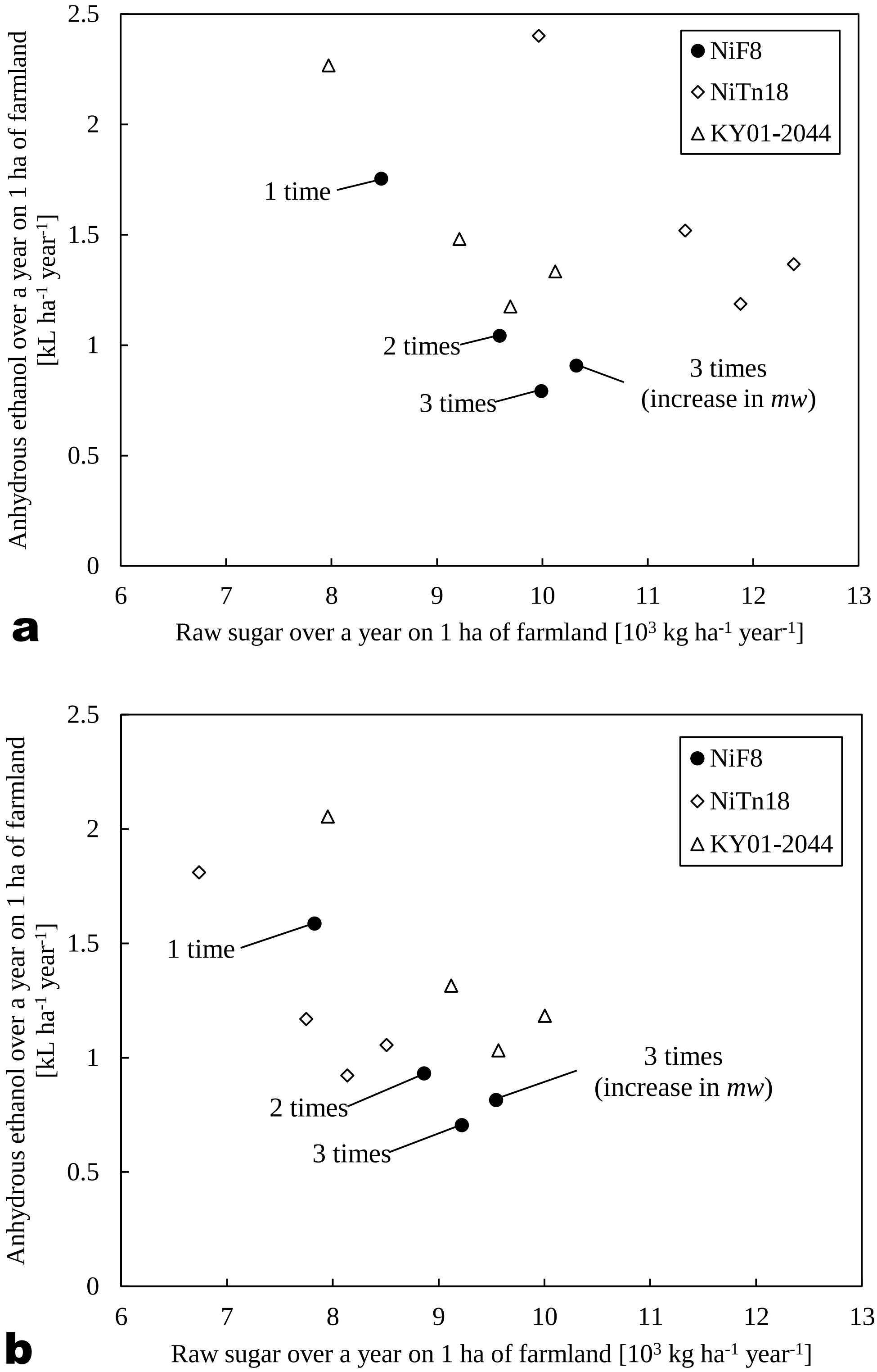


Figure 3-8 Raw sugar and anhydrous ethanol production. (a) Tanegashima case, (b) Tokunoshima case.

Figure 3-9 shows the energy balance per FU in the factory. HPS is utilized for rotating power in the RM and the PCT with some unavoidable energy loss and cascaded LPS, which is used in other units. Even if LPS is in excess, it cannot be used for RM and the PCT because they require higher quality of heat resources than LPS. Figure 3-9 also shows the available energy contained in all bagasse generated in the factory. Comparing the cases, the increase of sugarcane yield can be recognized by the difference in available energy. Where total steam consumption is larger than available energy from bagasse, the energy shortage is covered by burning additional fuel oil A.

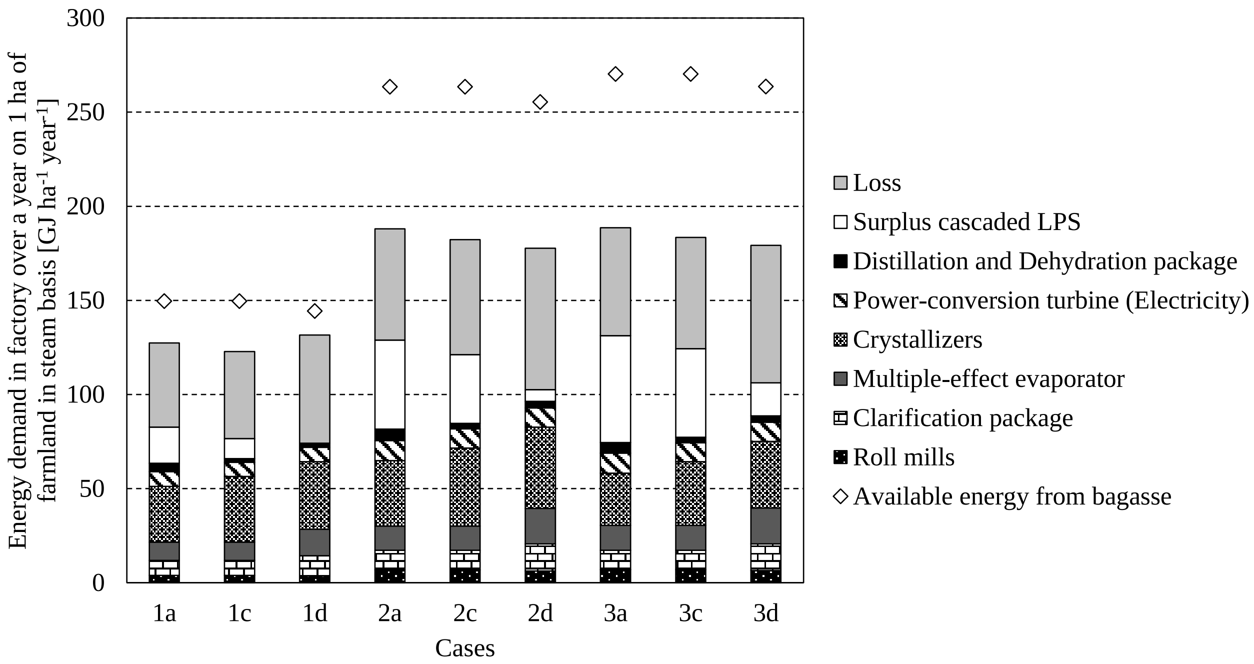


Figure 3-9 Detail of energy balance in factory. "Available energy from bagasse" represents the available energy if all generated bagasse is combusted.

It is clear that NiTn18 and KY01-2044 consume more total energy than NiF8 because they require more processing. However, they also produce more bagasse, which is enough to provide the energy necessary for the process while the bagasse from NiF8 may not supply all the energy of the factory without fuel oil A. Among the items, surplus cascaded LPS accounts for a large portion in most cases. This indicates that the ratio of demand of electricity to steam is greater in this cogeneration system that includes both sugar and ethanol production than in one that produces only sugar, and thus surplus LPS is produced by the PCT. It is important to note the destination of this LPS when interpreting the total energy consumption in the factory. As the number of crystallizations increases, the crystallizers require more energy, but the total energy demand does not always increase, as can be seen from Cases 1a and 1c. This is not only because the ethanol production shrinks as the sugar production increases, but also because the surplus LPS compensates the additional energy demands of the crystallizers. The same relationship applies to Cases 2c and 2d. The additional maceration water increases energy consumption after milling because of the increased processing, especially for evaporation and crystallization. However, this increment in consumption can also be compensated for by utilizing cascaded LPS. If surplus LPS is exhausted, this benefit will be lost, as in Case 1d. This operational modification brings further benefits, especially for high-yielding cultivars. As shown in Figure 3-8, the yields of raw sugar and anhydrous ethanol can be further improved by additional maceration water for all cultivars. In general, NiTn18 contains much fiber, which inhibits sucrose and brix extraction in the milling process. The increase in maceration water weakens this negative effect, and thus widens the range of choices to improve the yields of the products.

Figures 3-10a and b show the economic evaluation results for the agricultural and industrial sides, respectively. IFR stands for income from yielded sugarcane for farmers. The price of sugarcane is determined by its yield and sucrose content in Japan, as shown in Eqs (57)–(59). NiF8 has the highest sucrose purity among the three cultivars, but its yield and return are lower than those of the other two high-yielding cultivars. Industrial operations cost can be compared by IFC. Raw sugar profit accounts for a large portion in all cases, followed by the purchase cost of sugarcane, anhydrous ethanol profit, and credit from by-products. Other elements such as transport and utility expenses are not as significant as the above components for the entire system. Among the three cultivars, NiTn18 shows the highest IFC overall. Although its sugarcane purchase, transport, and labor cost are higher than the other two because of the increased weight, the high productivity of raw sugar and anhydrous ethanol shown in Figure 3-8a could outperform these disadvantages. The profitability of NiF8 is almost the same as that of KY01-2044. Figure 3-10b also shows the IFC if all by-products are given away for free, as they are in some Japanese regions. It can be seen that the credits from by-products play an important role for KY01-2044 in catching up with NiF8. For each cultivar, Case d, which recovers the highest amount of raw sugar by increasing maceration water, is the most profitable one. This is because the price of raw sugar per carbon weight is higher than that of anhydrous ethanol in this case study. It can be stated that profitability is better when more raw sugar is produced.

Figure 3-11 shows GHG emissions per farmland area per year throughout the lifecycle of raw sugar and anhydrous ethanol, where not only these main products, but also the by-products, i.e., crop residue, surplus bagasse, filter cake, and vinasse, are also considered. The emissions derived from the consumption of the products and the decomposition of the by-products are taken into account. As well as positive emissions, negative emissions such as CO_2 absorption by sugarcane during the growing stages and saving fuels and chemicals by the substitution of anhydrous ethanol and by-products are also calculated based on their carbon content or their inventory data for emission factors. The baseline of the graph stands for the present situation that gasoline and fuel oil A are consumed as usual over a year. If the net GHG emissions is negative, it shows that the substitution effects surpass the emissions from fossil fuels.

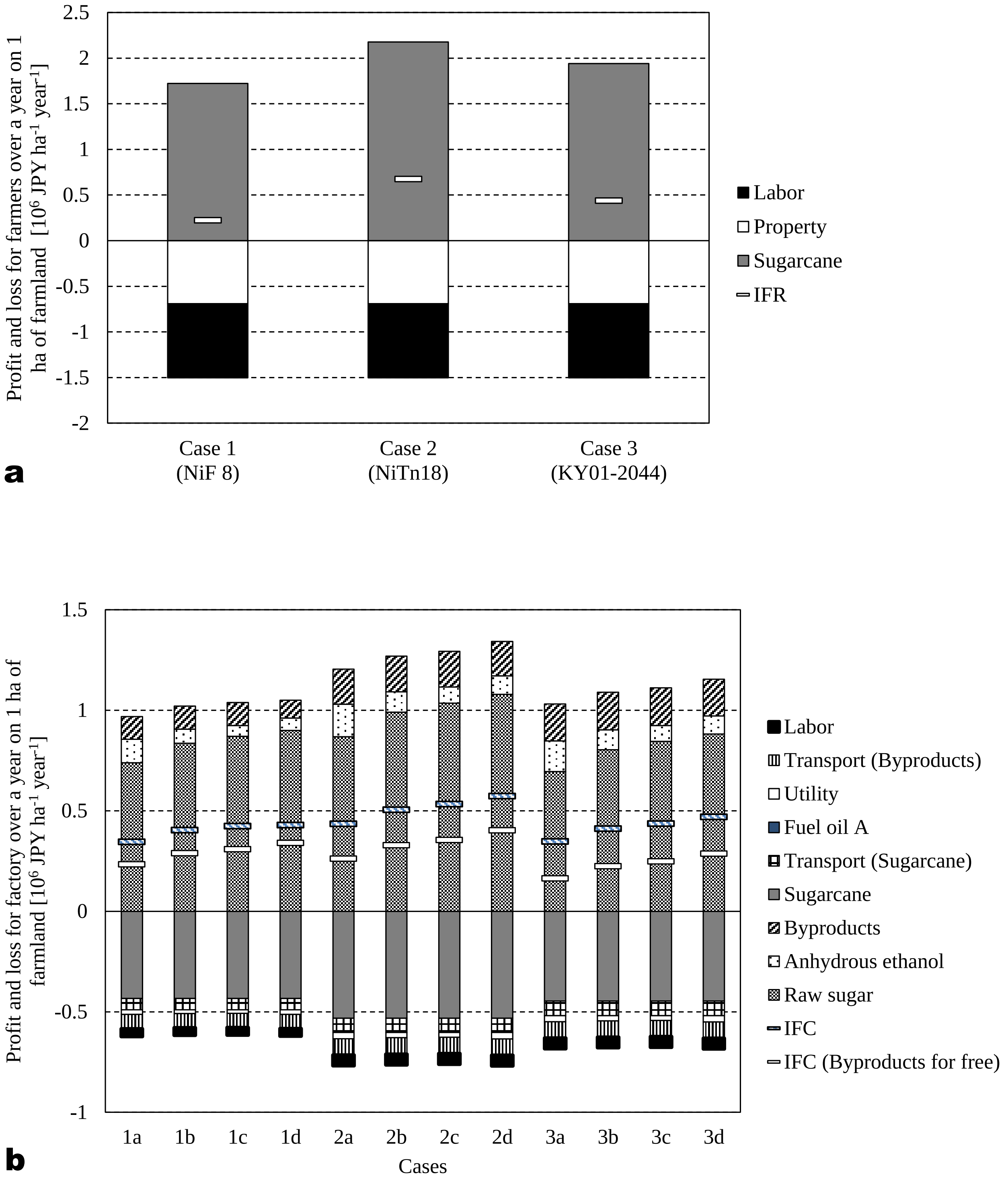


Figure 3-10 (a). Economic evaluation result of agricultural side. IFR is the income per farmland area per year for farmers. (b). Economic evaluation result of industrial side. IFC is the income per farmland area per year for factory. IFC where by-products are sold for free is also shown.

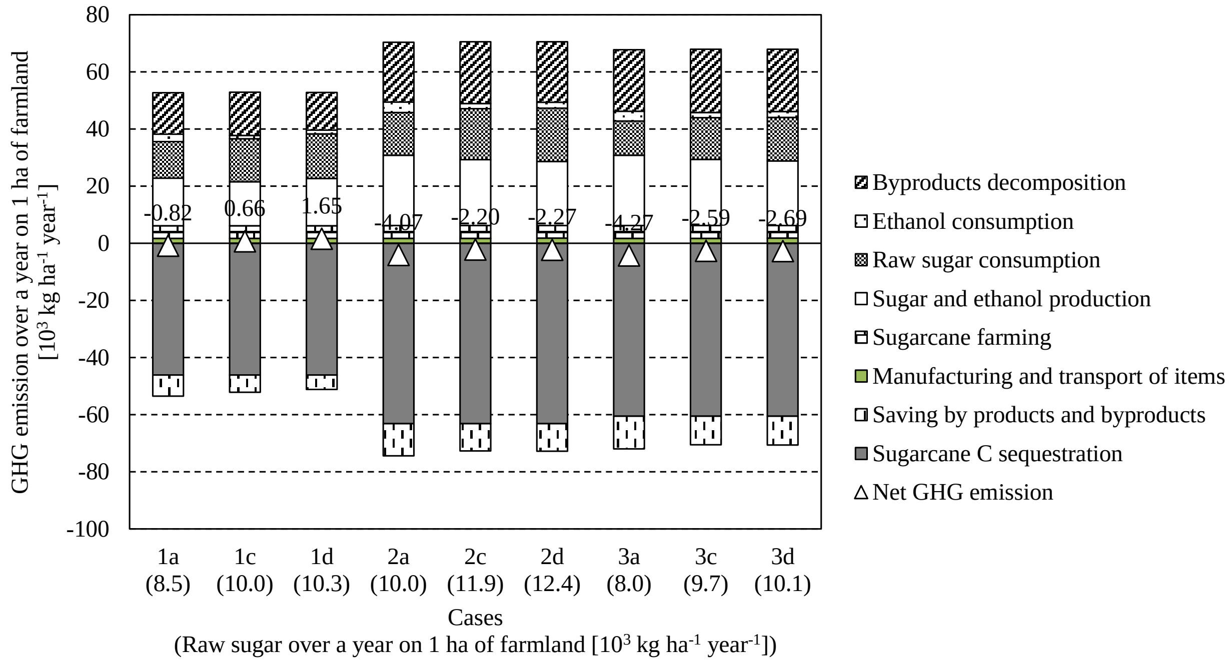


Figure 3-11 GHG emissions per farmland area in Tanegashima in the case study.

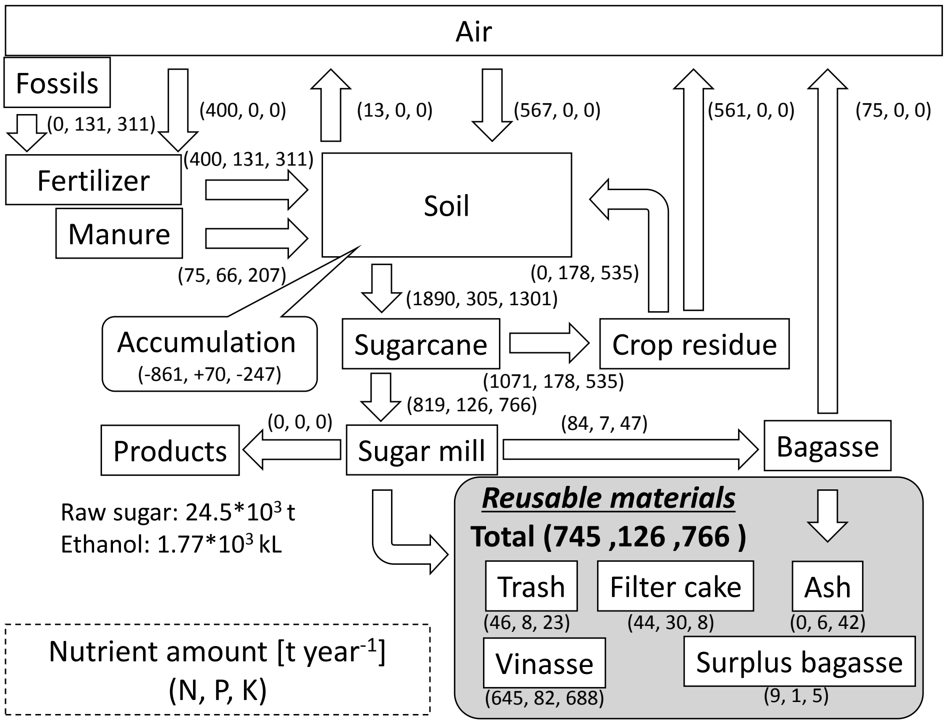
In all cases, the positive emissions are almost canceled by the negative ones. The emissions from sugarcane farming, manufacturing, and transport of the input items for farming and processing include GHG derived from fossil fuels or soils, and account for a small portion of the positive emissions in all cases. In other words, most of the positive emissions originate from material created using CO_2 from the atmosphere; therefore, the replacements are keys for differentiation among the cases. NiF8 has the largest amount of GHG emissions among the three cultivars. This is because the other two cultivars produce more anhydrous ethanol and by-products and, as a result, substitute more items than NiF8 does. It should be noted that the results here are based on the FU of the annual yield per unit area and rather different conclusions may be obtained if the FU is changed. For example, the amount of raw sugar produced in each case is quite different, as shown in the horizontal axis of the figure. In that respect, the FUs of all cases are different, which may induce other discussions of this result (see Chapter 3.2.5).

Mass balance of NPK for Case 1c and Case 2c was evaluated as shown in Figure 3-12. In this evaluation, the raw sugar production in Case 2c was adjusted to that in Case 1c by drawing off part of the cane juice to feed the fermentation process without going through evaporation and crystallization processes. Farming area was set as 25 km^2 based on the statistical data. With regards to NPK inputs other than fossil resources, nitrogen fixation from the air in Case 2c is larger than that in Case 1c. For these aspects, Case 2c looks more environmentally-friendly than Case 1c. However, focusing on output from the soil, NiTn18 deprives the soil of a large amount of nutrients and the soil becomes sterile in N and K. Some K can be recovered by way of the decomposition of crop residue, whereas no N can be recovered. Most of the nutrients in sugarcane flow to by-products from the sugar mill such as trash, filter cake, ash, vinasse and surplus bagasse, but some N is emitted to the air via the bagasse combustion. These by-products can be returned to the farmland as nutrient suppliers with direct spraying or taking some appropriate detoxification procedures. The amount of K in them is sufficient to maintain the soil fertility, while, as for N, effective use of crop residue before decomposition as well as the by-products is necessary to avoid the soil degradation in both cases.

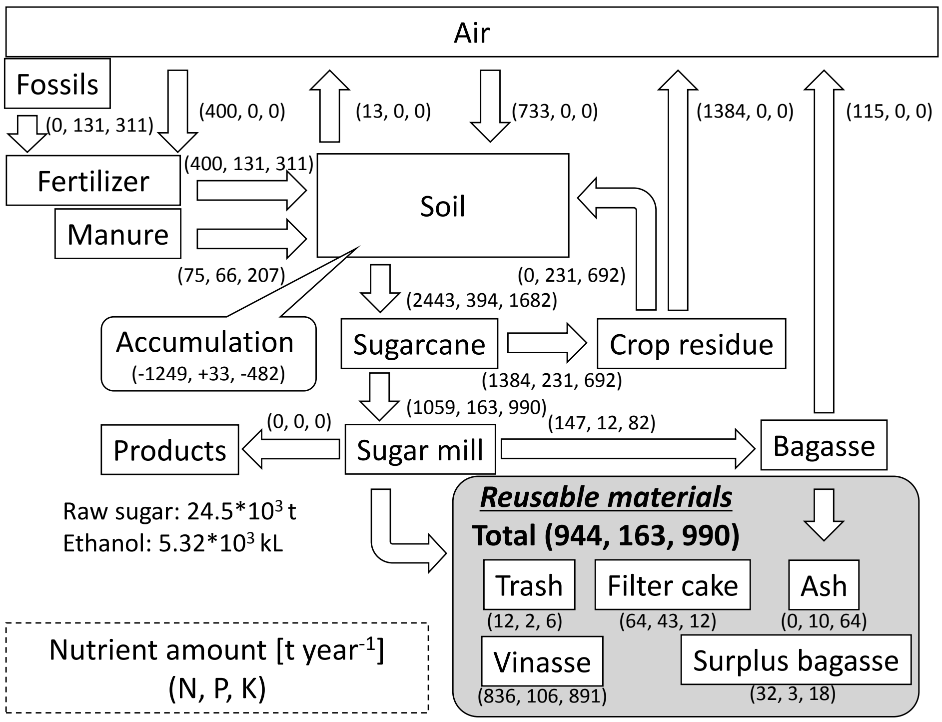
3.2.5. Discussion

High-yielding cultivars such as NiTn18 and KY01-2044 have not been favored by Japanese sugarcane industries because of their low sucrose content and difficulty of crop management, especially in harvesting. However, the results of this case study indicate that they can provide leaps in the productivity of raw sugar and ethanol without increases in fuels, facilities, and environmental loads, by adjusting industrial options such as the number of crystallization steps. These two cultivars can also offer more options for the operators of the factory than NiF8 can, because of the surplus bagasse shown as the gaps between plots and total energy consumptions in Figure 3-9. For example, it can be used as an energy utility in other ways, such as generating steam for evaporating the increased maceration water, as mentioned in the case study. The balance of the utilization of steam and electricity should be carefully examined and designed to minimize the waste of energy from the bagasse-derived combined heating and power system. Industrial symbiosis centering on sugar mills may contribute to regional energy management with renewable resources (Kikuchi et al., 2016b). In this regard, massive amounts of unused heat may not always be desirable, especially when there is no additional heat demand in the sugar mill or the adjacent area. Transporting this surplus heat to other places with, e.g., chemical heat storage, where a steam adsorption and desorption cycle of zeolite is employed, can be an alternative to overcome this spatial and temporal problem (Fujii et al., 2015).

The high-yielding cultivars appear to be at a disadvantage in terms of the soil fertility. Because their yields are usually higher than that of NiF8, larger amount of NPK in the soil are carried out from the farmland with crops, causing the loss of the soil nutrients. However, most of them move to by-products from the cane sugar mill and are recoverable if they are appropriately dealt with. Therefore, it is possible to maintain the soil fertility without additional chemical fertilizers if their appropriate handling is implemented with the cultivar change simultaneously.



(Case 1c)



(Case 2c)

Figure 3-12 Evaluation results of productivity and mass balance of NPK. (Case A) NiF8 and 3 times crystallization, (Case B) KF92-93 and 2 times crystallization.

If we consider optimization from the viewpoint of the three aspects, i.e., productivity, GHG emissions, and economics, Case 1d seems to be the most beneficial and acceptable one of the 12 cases studied. It should be noted that some practical points might be missed in the current evaluation. Although the FU in this case study, annual yield per unit area, is easily understandable for sugarcane farmers and factories, it does not completely reflect actual conditions. In general, ratooning is repeated several times after a year of new planting, and fallowing is sometimes inserted between ratooning and the next new planting. The characteristics of ratooned sugarcane depend on ratooning times and cultivars (MAFF, Japan, 2014; KARC, 2004; KARC, 2010). Fluctuations in quantity and quality of the crops may have an influence on the industrial side and result in rather different outcomes. The temporal boundary should be extended to several years including ratooning and fallowing for more precise evaluation. Ratooning more than once was not considered in this case study because we faced data limitations. It should be recommended that sugarcane growth data after the first ratooning year should be intensively stored in agricultural institutes.

In addition, the interpretation of the results of GHG emissions can vary depending on their method of allocation (Soam et al., 2015). Because the target process system in this paper has multiple potential products (i.e., raw sugar, anhydrous ethanol, surplus bagasse, and renewable energy), the environmental loads attributable to the process system should be allocated to those products; otherwise, the comparison among the alternative cases is less fair. Figure 3-13 shows the GHG emissions based on ethanol production instead of per unit area for the case that produced more raw sugar than Case 1c (the base case) in the case study, as shown in Figure 3-11. The amount of raw sugar produced was adjusted to that in Case 1c by drawing off part of the clear juice to feed the fermentation process without going through evaporation and crystallization processes. An energy content-based partitioning technique was applied to allocate the emissions between raw sugar and anhydrous ethanol for each case. Unlike Figure 3-11, only emissions for raw sugar and anhydrous ethanol were evaluated: Emissions after production, absorption by sugarcane, and savings by substitutions were excluded and CO_2 emissions derived from trash and bagasse combustion and fermentation were regarded as carbon neutral. Figure 3-13 shows that the GHG emissions in Case 1c is 867 kg kL^{-1}. According to Silalertruksa et al. (2009), the GHG emission of anhydrous ethanol production in Thailand was 654 kg kL^{-1} based on the same allocation approach based on energy content. Khatiwada et al. (2011) also reported that the emission is 407 kg kL^{-1} in their Nepalese case caluculated by economic allocation, while that for our Case 1c is 667 kg kL^{-1} if calculated with the same allocation approach. Clearly, these results strongly reflect the intensive Japanese inputs of fossil energy into farming. Although the overall configuration of the graph in the figure is rather different from that in Figure 3-11, high-yielding sugarcanes still have advantages. While the food, i.e., raw sugar, must be the first priority, the priorities among the others are unclear. They can be utilized as substitutes for fossil fuels, leading to reductions in GHG emissions. The FU of LCA significantly dominates the final results and their interpretation. Careful consideration of the transparency settings of FUs is necessary for robust decision-making on the enhancement of the achievements by sugarcane-derived production.

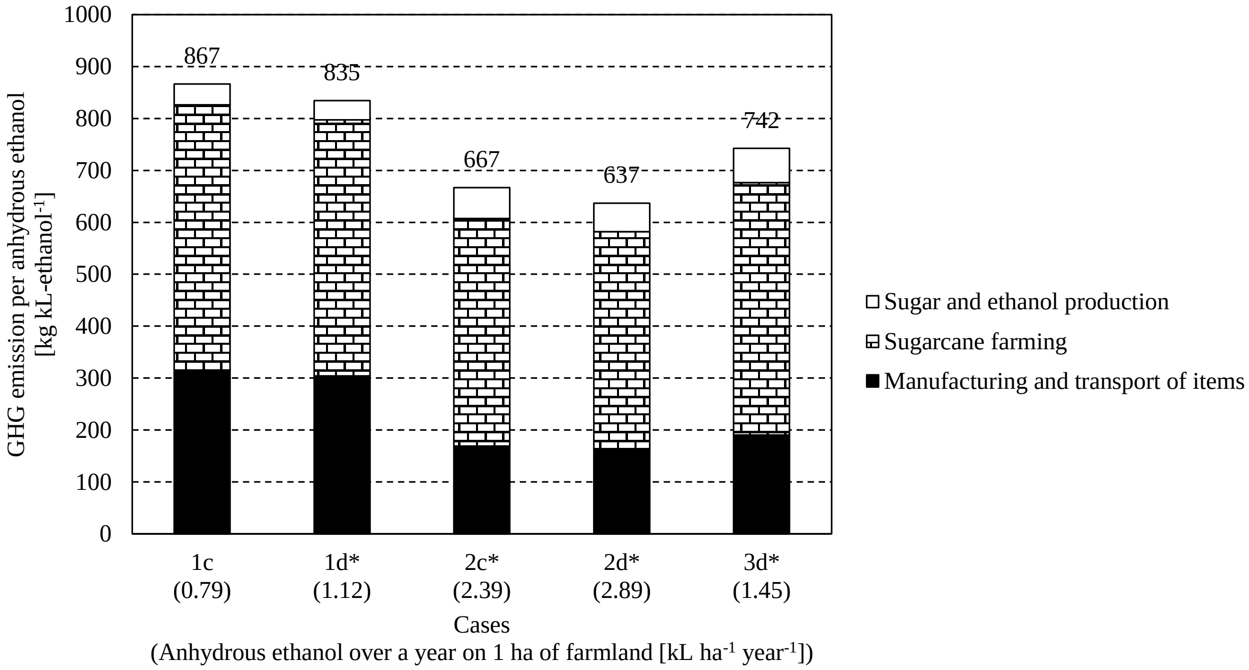


Figure 3-13 GHG emissions per ethanol production in Tanegashima in the case study. *Raw sugar production is adjusted to the amount in Case 1c.

Paying attention to the abovementioned points, new solutions for improvement can be discovered by analyses integrating agriculture and industry. Nevertheless, such approaches have not been sufficiently explored. According to Figure 3-10a, it appears that farmers can achieve the transition from conventional cultivars to high-yielding ones by themselves because an increase in farmers' sales can be expected. However, it should be noted that in reality their decision-making is not only influenced by economic factors but also by policies, sometimes resulting in conflicts of interests with sugar mills. In addition, this case study did not consider other factors such as operability and production stability toward disease and insect and storm damage. For example, the leaves of NiF8 are easy to remove, while those of NiTn18 and KY01-2044 are difficult to strip off (MAFF, Japan, 2014; KARC, 2004), which reduces the working efficiency of harvesting. In addition to the operability issue, NiTn18 and KY01-2044 are less resistant to smut diseases than NiF8. Thus, the competiveness of each cultivar has been interpreted considering these viewpoints as well as the economic benefits.

The integrated design again provides us some insights for overcoming this situation. When raw sugar is the only product from a factory, which is the present situation in Japan, the farmers and the factory fairly share the responsibility for productivity according to the Japanese policy: Farmers can increase their income if they produce sucrose-rich sugarcane, which improves productivity and profitability for the industrial side. Once values are added by ethanol and by-products, as in the case study, the industrial side will take the chance to profit from a wider variety of cultivars including high-yielding sugarcane and even sucrose-poor sugarcane, as shown in Figure 3-10b. Some of the factory profit may be gained at the expense of farmers' efforts. Price-decision procedures for sugarcane and final products should be discussed together, involving both the agricultural and industrial sides for desirable decision making.

In reality, the decision making of Japanese sugarcane farmers has been subject to the SYM, which is a one-equation method for evaluating the quality of sugarcane produced on farming land (Yamane, 1967). While the simple SYM method has been supported by farmers to date, it cannot incorporate the effects of measures that industrial operators may take to enhance their productivity after sugarcane shipment. As the case study shows, modifications of industrial operations such as maceration water handling, crystallization steps, and bagasse usage can have great impacts on productivity after incorporating agricultural options. The process model developed in this paper has the potential to replace SYM as an evaluation tool. The model can simulate the effects of industrial operations more precisely than SYM with a user-friendly estimation procedure. Table 3-12 compares the results of total and SYM raw sugars and shows that some cases have higher values in simulation results than SYM, which is significant in the cases including increased maceration or high-yielding cultivars. Especially with high-yielding cultivars, the gaps between the simulations in this paper and SYM are quite large for qualifying sugarcanes. Implementation of this model in the sugarcane industry will enable us to review the most desirable options for both sides from holistic viewpoints, given that the optimal point depends on the environmental and social conditions. It may also change the decision-making of the stakeholders and direct them toward more productive systems. Otherwise, worse choices of cultivars may be made.

The process model constructed in this section is a starting point and allows various applications in its current form. As long as solutions are sought under the limited objective functions, it seems possible to identify optimal or near-optimal points. However, objective functions themselves should be specified in accordance with local situations. The model should be evolved continuously to analyze changing effects. The current model was developed based on the available data and knowledge of the past and, therefore, does not reach a level that gives us reliable information. For example, this model cannot perform dynamic simulations. At actual sugar mills, changing feedstocks, maceration water handling, or crystallization steps may cause scheduling problems in downstream processes. Agricultural sites also require temporal analyses because timings of planting and harvesting depend on individual decisions by each farmer, resulting in ad hoc management, while such farming operations should be managed strategically based on the growth of the sugarcane. Introducing detailed temporal profiles into the simulation model will allow discussion that is more realistic. Unfortunately, insufficient data are available for dynamic simulations, especially in agriculture. The importance of systematic accumulation of data by related researchers must be recognized for further development of the model. Simulations based on the developed model may facilitate such new actions for interdisciplinary analysis. The results of the case study emphasize the potential of such preliminary analysis. In conclusion, an integrated modeling approach presented in this section can support exploring the alternative strategies for the improvement of process systems including agriculture, not only industries.

3.3. Alternative Generation Considering Technology Introduction

3.3.1. Applicable Technology Options

In Chapter 3.2, choosing high-yielding cultivar such as NiTn18 and KY01-2044 are proposed to enhance the systems performance. Practicing this proposal, however, still has some challenges. For example, cane juice extracted from the high-yielding cultivars that have been developed only for sugar production have different compositions that could disturb sugar crystallization procedures that were developed for conventional cultivars, and lower the operability. In some Asian sugar mills, a three-boiling system (Yamane, 1967), which comprises complex recycling of molasses and sugar, is adopted to exploit as much sugar as possible. A drawback of this system is the complex scheduling that the operators have to deal with. While the operators wish to make full use of available crystallization pans to secure sufficient time for growing sugar crystals, they also have to seamlessly take care of the batch schedule of the crystallization pans, crystallizers, and centrifugal separators, as well as the tank volume for receiving the syrup that is continuously accumulated from upstream processes, all at the same time. Some operation conditions such as the mixing ratio of syrup, molasses and seeds for crystallization are controlled in a manner that strongly depends on the operators' heuristics. In particular, the highest concern is the elevated composition of glucose and fructose (reducing sugars: RS) in the cane juice as it hinders sucrose crystallization. Plant breeding cannot easily live up to all these demands including a high unit yield, desirable compositions and resistance at the same time without giving up any of its properties (Tilman et al., 2011). The question of how a large change in the composition of cane juice may affect production efficiencies is subject to high uncertainty, and a simple mass and energy balance-based simulation (Ohara et al., 2009) cannot address this practical concern.

To overcome this disadvantage, the inversion process, which introduces selective fermentation (SF) of RS between clarification and evaporation as a retrofitting design, was proposed (Ohara et al., 2012). Yeasts incapable of using sucrose selectively convert RS into ethanol (Ohara et al., 2013; Kato et al., 2015), which is inevitably removed in the subsequent evaporation process, and thus concerns over the complication of sucrose crystallization procedures disappear and the efficiency of sugar recovery can be improved. Furthermore, the residual sucrose in molasses is decreased and the molasses that has to be recycled is also reduced. This allows operators to spare more time on each batch instead of exploiting the residual sugar from molasses. Thus, new sugarcane cultivars such as those containing high RS for the sake of achieving high unit yield become available as feedstock because of this technology. In other words, SF can achieve outcomes similar to successful yield improvement that has been achieved only by breeding in the past.

The advantages of SF, however, should be addressed carefully because it is a new technology that has not been installed into sugar mills yet. The benefits regarding the total product yield and the operability of the crystallization process depend strongly on the conditions of the crops in that year. In addition, the cost of additional investment such as heat exchangers required for installing SF in the conventional process strongly depends on the hot and cold energy availability in the mill. In a design stage of retrofitting SF in an existing sugar mill, a modeling approach should be helpful for identifying desirable and feasible alternatives considering the relationship among uncertainties in agriculture, system performance, and required capital investment.

In this section, the system-wide effects on the productivity, operability and profitability are examined for a coordinated transformation of cultivars in the farm and process operation in the sugar mill, assisted by the introduction of SF. To compare the proposed process to the current one, SugaNol, which is developed in Chapter 3.2, is extended to include SF. Using the extended model, a case study on a cane sugar mill in Tanegashima, which is one of the islands in Japan, is performed to compare the performance of the proposed and the current process for two cultivars, one for sugar production and one for combined sugar and ethanol production. Through this case study, the advantages of installing SF, regarding the yield of final products and the operability of the crystallization process, are examined when the latter cultivar is chosen. Furthermore, the specific characteristics of cultivars to make SF economically feasible are studied to present a guideline for future cultivar development.

3.3.2. Model Extension for Simulation Considering Selective Fermentation

SugaNol model, which have been developed in Chapter 3-2, should be extended to discuss the merits and demerits of installing SF into a sugar mill quantitatively. Through the extended work, this model should be able to quantify the changes in mass and energy flow caused by inserting SF between the clarification and evaporation processes, as well as the size of equipment, such as fermenters and culturing tanks. As SugaNol is a static model, the temporal limitation from the scheduling of crystallization pans could not be considered. Nevertheless, it was possible to estimate the minimum total time required for boiling the total feeds in each crystallization stage through one season.

The data and information about SF and crystallization processes were collected from the literature (Ohara et al., 2012) and the operation record of the pilot plant installed in the actual sugar mill. Additional data about sugarcane cultivar was also investigated. The concentration of RS and other brix in cane juice were inspected for each cultivar to compensate for information lacking in existing reports.

Figure 3-14 shows the conventional (Conv.) process of combined sugar and ethanol production and the proposed process (Inversion process and hereinafter referred to as “Inv. process”). A dialed explanation of the Conv. process is described in Chapter 3-2-3. Inv. process includes SF between the clarification and evaporation processes. This position is considered to be appropriate for the following reasons. SF must be at least placed before the crystallization process to improve its efficiency. Syrup is not suitable as the raw material of fermentation because its brix concentration is too high for the strain to initiate metabolism, while the extraction of the juice from either multiple-effect evaporator is also difficult to use from an operability aspect. It cannot be recommended to use the cane juice just after the milling process because some components in the juice affect the SF process. It contains microbes such as yeast, bacteria and fungi that convert carbohydrate into ethanol, lactic acid, and polysaccharide (Eggleston, 2002), which may contaminate the flow in SF fermenters. In addition, some suspended solids in the juice could be precipitated in fermenters as scales. On the other hand, some microbes be killed through juice heating and some solids can be partly removed by precipitation and filtration before evaporation. This is why the juice after clarification is the best material for SF.

The mainly targeted process modules extended in this section are represented as dotted lines and a box in the figure. In the case of the Inv. process, stream ISin, ISout and ISd1 are activated instead of stream I3. Some modules of other processes in addition to SF such as clarification, evaporation and crystallization were refined. The technology option of whether SF is installed or not, and the type of heat exchangers and chillers must be added as input parameters. The equations related to the model extension are expressed below.

Physicochemical parameters

The physicochemical properties of clear juice and fermentation liquor can be estimated as the solution in cane sugar mills as reported by Rein (2007). The density, heat capacity, and thermal conductivity are estimated as Eqs.(61)-(63), respectively;

$$\rho = \left(1 + \frac{w_{\mathrm{bx}} \cdot (w_{\mathrm{bx}} + 200)}{54000}\right) \cdot \left(1 - \frac{T - 20}{160 - T}\right) \quad (61)$$

$$c_j = 4.1868 - w_{\mathrm{bx}} \cdot (0.0297 - 4.6 \cdot 10^{-5} \cdot Pur) + 7.5 \cdot 10^{-5} \cdot w_{\mathrm{bx}} \cdot T \quad (62)$$

$$\lambda = (1 - 0.54 \cdot w_{\mathrm{bx}}) \cdot \left(0.561 + 0.206 \cdot \frac{T}{100} - 0.0943 \cdot \left(\frac{T}{100}\right)^2 - 0.007746 \cdot \left(\frac{T}{100}\right)^3\right) \quad (63)$$

where w_{bx} is the mass fraction of brix, Pur is purity, and T is temperature [°C]. In addition, dynamic viscosity of sucrose solution [$\mathrm{Pa \cdot s^{-1}}$] is also estimated as the function of mass fraction of sucrose, w_{suc}, and temperature (Rein, 2007). Based on this physicochemical estimation, the heat exchanging is simulated by the following mechanism.

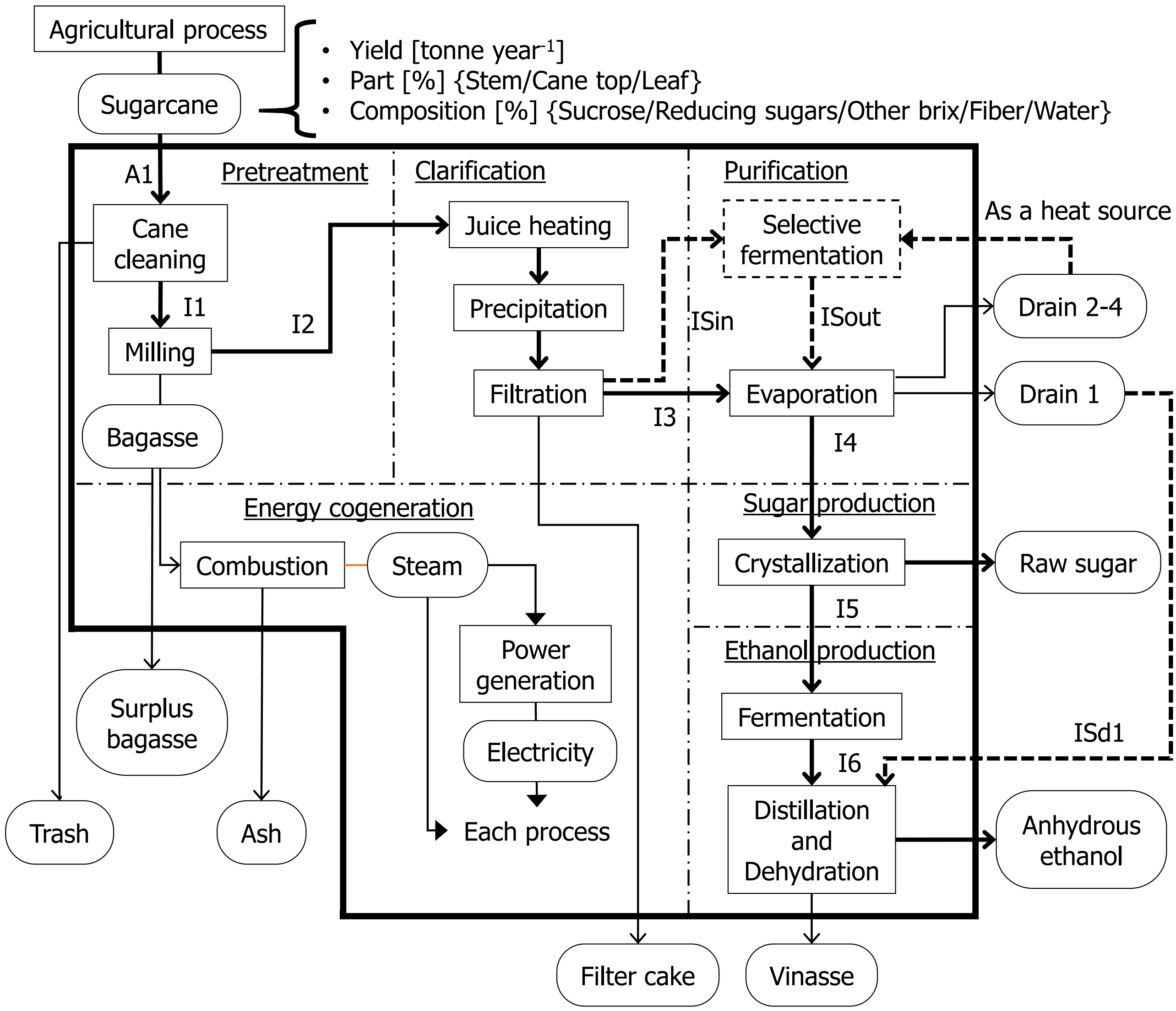


Figure 3-14 Process flow diagram. In the Inv. process, the dotted box and arrows are activated instead of stream I3.

Clarification process

Some sucrose decomposes into RS through clarification process because of acidic conditions and *invertase* (Vukov, 1965) in the raw juice. The decomposition ratio is defined as $Xcl_{\mathrm{suc}\rightarrow\mathrm{red}}$. This parameter should be specified for each mill because it strongly depends on pH and temperature, which may vary among the mills. The cane juice is heated through two heat exchangers. First, it is heated to $T_{\mathrm{JH}(1)}$ through the primary heat exchanger, the heat source for which is the extracted steam between the fourth and the fifth evaporators in the evaporation process (see Figure 3-17). Next, the juice is further heated to $T_{\mathrm{JH}(2)}$ through the secondary heat exchanger. The secondary heat source is low-pressure steam (LPS) that is cascaded from the roll mill (RM) turbine or the power conversion turbine (PCT).

Heat exchanger

Figure 3-15 shows the overview of heat exchanger (HEX) network in Inv. process. This network is composed of five heat exchanger units, i.e., heat exchanger (HEX) and heating/cooling facilities for utilities (HF/CF). The first unit, HEX1 and CF1, lowers the temperature of the input stream of HEX1, $T_{\mathrm{ip}}^{\mathrm{HEX1}}$ to $T_{\mathrm{op}}^{\mathrm{HEX1}}$ before selective fermentation. Electric or absorption chillers are required for CF1, where the coolant is cooled to 7°C from 12°C based on the literature (Saito, 2000). The second unit, HEX2 and HF2, reheats the fermentation liquor from $T_{\mathrm{ip}}^{\mathrm{HEX2}}$ to $T_{\mathrm{op}}^{\mathrm{HEX2}}$, which is returned to the evaporation process in sugar mills. As described in Chapter 3.2.3, LPS is available as HF2. The steam is transferred to the reboiler as in an actual sugar mill (Kikuchi et al., 2016b). These two units, which have the role of adjusting the temperature for fermentation and evaporation, are indispensable for the introduction of SF. To meet the constraints of temperature adjustment by these two units, $T_{\mathrm{ip}}^{\mathrm{HEX1}}$ and $T_{\mathrm{ip}}^{\mathrm{HEX2}}$ are given from the temperature of clear juice and SF liquor, respectively.

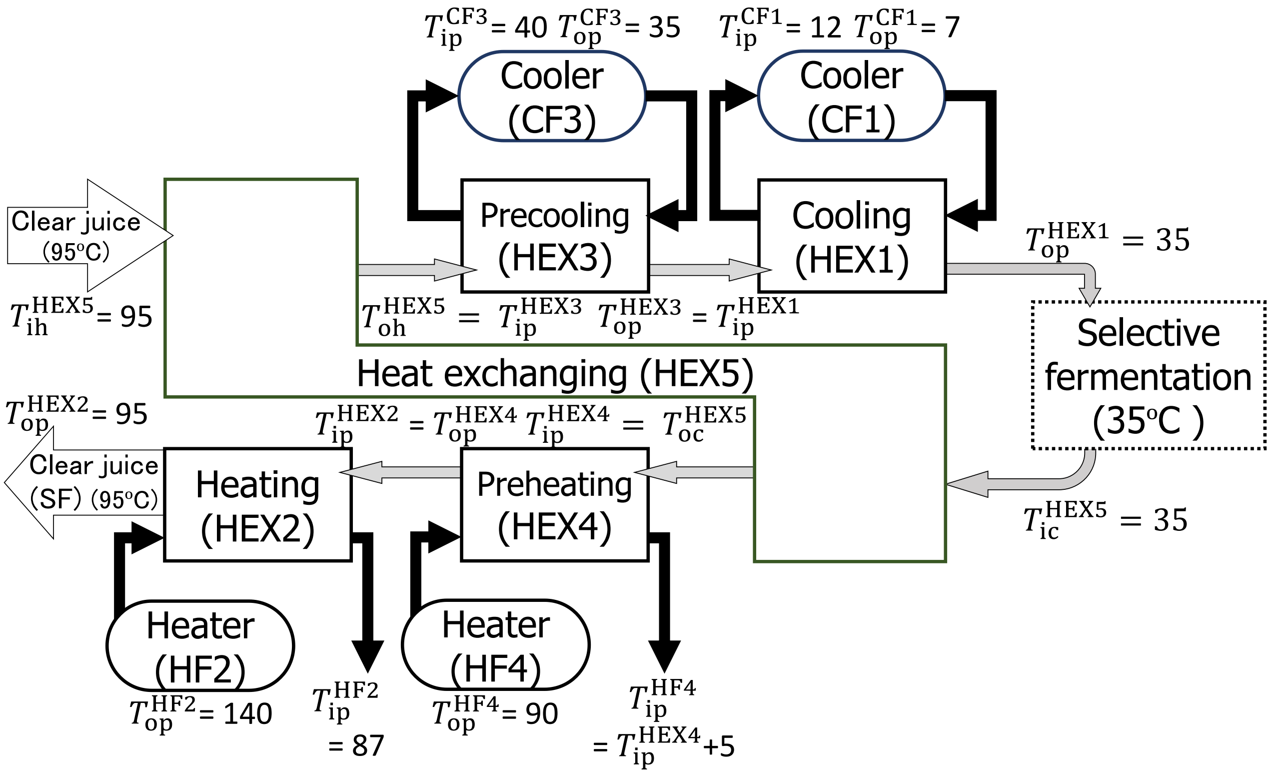


Figure 3-15 Superstructure of the heat exchanger network before/after selective fermentation. The solid-line units are scoped in this study. The boxes and rounded-corner boxes are heat exchangers and utility devices, respectively.

The remaining three units in Figure 3-15 are optional to save power and steam. The third unit, HEX3 and CF3, can be applied to save cooling duty in the first unit (HEX1 and CF1). The coolant at $T_{\mathrm{ip}}^{\mathrm{CF3}} – T_{\mathrm{op}}^{\mathrm{CF3}}$°C is acquired from a cooling tower. Defining the minimum approaching temperature at 5°C, the output stream from HEX3, $T_{\mathrm{op}}^{\mathrm{HEX3}}$ (=$T_{\mathrm{ip}}^{\mathrm{HEX1}}$), is cooled to 95–40°C. Introduction of the third unit reduces the cooling duty in HEX1, which cuts down power or steam consumption for electric and absorption chillers serving as CF1. The fourth unit, HEX4 and HF4, reduces the heating duty in the second unit (HEX2 and HF2). In sugar mills, abundant waste hot water at 70°C is readily available (Kikuchi et al., 2016b). This waste hot water is mixed with low-pressure steam to yield 90°C hot water used for the hot heat source in HEX4. Defining the minimum approaching temperature as 5°C, the output stream from HEX4, $T_{\mathrm{op}}^{\mathrm{HEX4}}$ (=$T_{\mathrm{ip}}^{\mathrm{HEX2}}$), is heated to 35–85°C. The fifth unit, HEX5, exchanges heat between clear juice and fermentation liquor to trim further the hot/cold heat demand. Defining the minimum approaching temperature as 15°C, the output hot stream from HEX5, $T_{\mathrm{op}}^{\mathrm{HEX5}}$ (=$T_{\mathrm{ip}}^{\mathrm{HEX3}}$), is cooled to 95–50°C.

The type of HEXs were selected on the basis of streams used as hot or cold ones (Obana, 2011). HEX1, HEX2, HEX3, and HEX4 have sucrose solutions and water as their streams. Because liquid water and LPS can be regarded as non-viscous fluid adequately, shell and tube (S&T) HEXs were adopted. On the other hand, both streams passing through HEX5 are sucrose solutions, which may be regarded as viscous and impurity-rich fluids. For facilitating the maintenance of HEXs, a spiral (Sp) HEX, a kind of plate HEXs, was selected for HEX5.

The heat transfer was mathematized as follows;

$$\frac{1}{U} = \frac{1}{h_o} + r_o + \frac{D_o}{D_m} \cdot \frac{wd_w}{\lambda_w} + r_i \cdot \frac{D_o}{D_i} + \frac{1}{h_i} \cdot \frac{D_o}{D_i} \tag{64}$$

where U is the overall heat transfer coefficient, h_o and h_i are the outside and inside film heat transfer coefficients, respectively, r_o and r_i are the surface contamination factor of outside and inside wall for heat exchanging, respectively, D_o, D_i, and D_m (= $(D_o - D_i)/\ln(D_o/D_i)$) are the outside, inside, and average diameters, respectively, d_w is the width of wall, and λ_w is the thermal conductivity of wall. The coefficients of heat transfer were estimated with empirical models. Regarding S&T HEXs, the following Chen's (Chen et al., 1946), Eq. (65), and Wiegand's equations (Wiegand, 1945), Eq. (66), were utilized in laminar and turbulent flows of shell, respectively (Obana, 2011).

$$\frac{h\prime \cdot D_\theta}{\lambda} = 1.02 \cdot Re^{0.45} \cdot Pr^{0.5} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \cdot \left(\frac{D_\theta}{Lt}\right)^{0.4} \cdot \left(\frac{D_{si}}{D_o}\right)^{0.8} \cdot Gr^{0.05} \tag{65}$$

$$\frac{h\prime \cdot D_\theta}{\lambda} = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot \left(\frac{D_{si}}{D_o}\right)^{0.45} \tag{66}$$

where D_θ is the representative diameter, D_{si} the inner diameter of shell, μ_w is the dynamic viscosity on the surface of wall, and Lt is the tube length. The coefficient of tube flow was calculated from the Eq. (67), where j_H is the heat transfer factor obtained as a function of Reynolds number

(Obana 2011).

$$\frac{h\prime \cdot D_i}{\lambda} = j_H \cdot Pr^{1/3} \cdot \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (67)$$

The following Dravid's (Dravid et al. 1971), Eq. (68), and Sander's equation by Hargis et al. (1967), Eq. (69), were utilized in laminar and turbulent flows, respectively in Sp HEX (Obana 2011).

$$h = \left(0.65 \cdot Re^{0.5} \cdot \left(\frac{D_\theta}{D_H}\right)^{0.25} + 0.76\right) \cdot \left(\frac{\lambda}{D_\theta}\right) \cdot Pr^{0.175} \quad (68)$$

$$h = \left(0.0315 \cdot Re^{0.8} - 6.65 \cdot 10^{-7} \cdot \left(\frac{Ls}{b}\right)^{1.8}\right) \cdot \left(\frac{\lambda}{D_\theta}\right) \cdot Pr^{0.25} \cdot \left(\frac{\mu}{\mu_{\mathrm{w}}}\right)^{0.17} \quad (69)$$

where Ls is the stream length. Because the steam utilized in HEX2 is superheated steam, the coefficients of heat transfer were obtained through a convergence analysis on the heat transfer areas of desuperheating and condensing zones inside HEX (Obana 2011). Although it was assumed that HEX1, HEX3, and HEX4 are double-pipe HEXs, multiple-pipe HEX was adopted for HEX2 (Obana 2011). Due to the temperature dependency of overall heat transfer coefficient, a thermal correction was built in the calculation of temperature of hot and cold streams (Obana 2011).

Selective fermentation process

Figure 3-16 shows the details of the SF process including heat exchanging. The fermentation type here is repeated-batch fermentation. This is because the most promising yeast strain recently developed for SF, called GYK-10 (Kato et al., 2015), has flocculent characteristics. Once the fermentation finishes, the yeast immediately settles to the bottom by gravity. This characteristic enables the yeast to be recycled for the next batch after simple extraction of the supernatant liquor, avoiding the cost of culturing additional yeast and yeast separators. Instead of enjoying these benefits, SF process requires at least three fermenters and their scheduling because the inlet and the outlet are continuous streams. First, the clear juice on stream ISin is received into the N_{SFM} fermenters where the yeast broth is prepared, and then fermentation is implemented under controlled temperature at 35° C. The conversions of reactants in the SF process are listed in Table 3-13, where $Xsf_{i1 \to i2}$ is the conversion ratio from i1 into i2. No sucrose is hydrolyzed, while RS is converted into ethanol, organic material, and yeast cells. After fermentation, the supernatant liquid is drained to the next process. The same amount of yeast as at the starting point is left in the fermenter and the incremental yeast and produced CO_2 are emitted as byproducts before moving on to the next fermentation. Enough yeast strains to be used in the fermenters are prepared in advance. The process of culturing the yeast, shown in the dotted box in the figure, requires yeast culture tanks and nutrients for their growth. This process is operated not only at the beginning but also at regular intervals to avoid the gradual deterioration of the yeast although the length of the intervals depends on the technology level of the yeast and the operation.

Table 3-13 Selective Fermentation Reactions, Conversion Symbols, and Values

Reaction	Reactant	Conversion
$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$	$C_{12}H_{22}O_{11}$	$Xf_{\mathrm{suc}\rightarrow\mathrm{red}}$ (=0)
$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$	$C_6H_{12}O_6$	$Xf_{\mathrm{red}\rightarrow\mathrm{etoh}}$
$C_6H_{12}O_6 \rightarrow$ Yeast	$C_6H_{12}O_6$	$Xf_{\mathrm{red}\rightarrow\mathrm{s,yeast}}$
$C_6H_{12}O_6 \rightarrow$ Organic material	$C_6H_{12}O_6$	$Xf_{\mathrm{red}\rightarrow\mathrm{org}}$

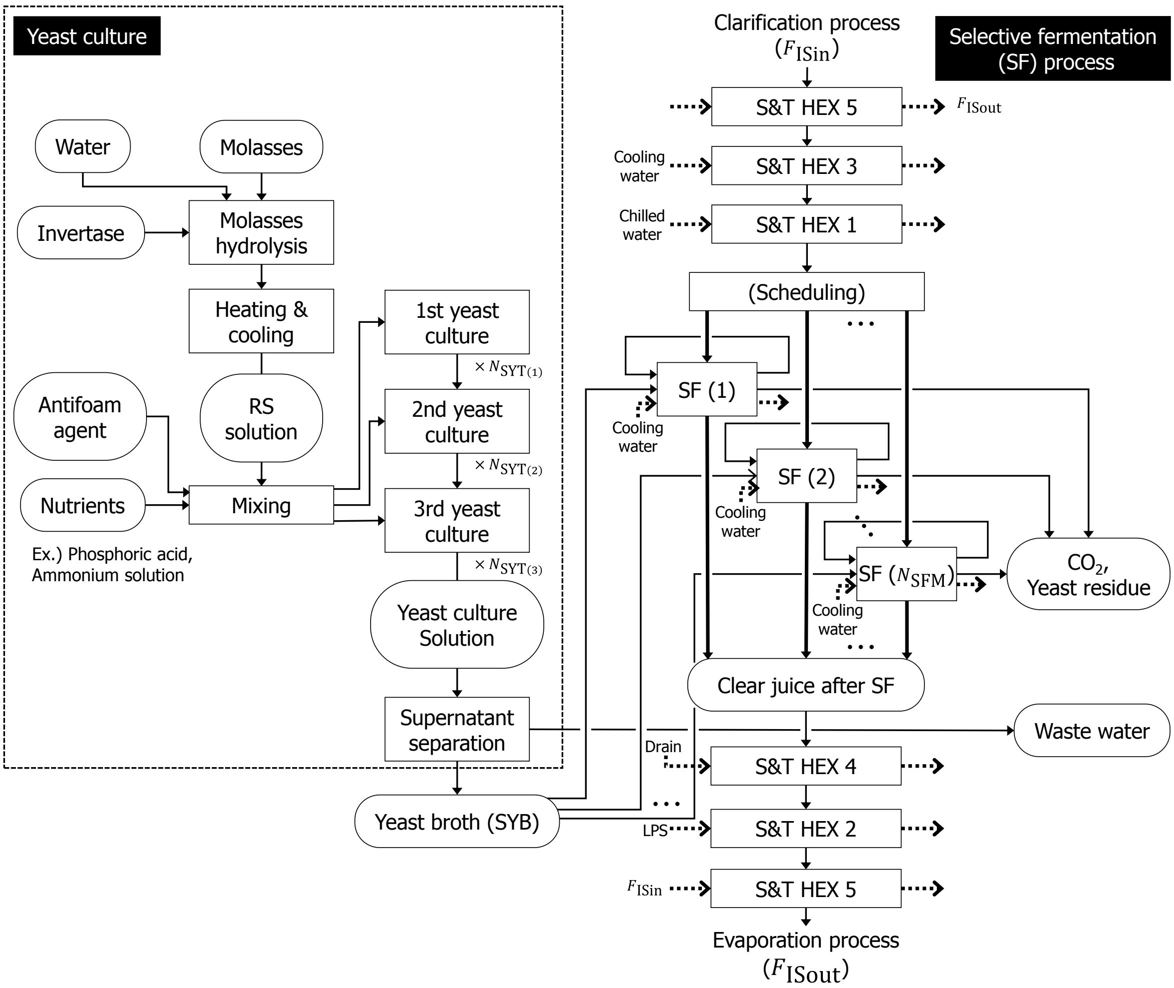


Figure 3-16 Process flows in the modeled SF process.

To estimate the demand of the yeast and the size of the tanks in Figure 3-16, the volume of fluid contained in them should be specified. The volume of the clear juice contained in one fermenter (FV_{CJ}) is given by:

$$FV_{\text{CJ}} = \frac{CT \cdot Fh_{\text{ISin}}}{\rho_{\text{CJ}} \cdot N_{\text{SFM}}} \tag{70}$$

where CT is one cycle time for SF, Fh_{ISin} is the flow rate of stream ISin, ρ_{CJ} is the density of the clear juice, and N_{SFM} is the number of fermenters. Assuming that the unit of Fh_j is 10^3 kg h^{-1}, Fh_j can be calculated as follows:

$$Fh_j = \frac{FA_j}{24OP} \tag{71}$$

where FA_j is the annual total mass flow of stream j, and OP is operating days of the cane sugar mill. FA_j is given by:

$$FA_j = F_j \cdot Af \tag{72}$$

where Af is the farmland area. OP is calculated by:

$$OP = \frac{FA_{\text{A1(cane)}}}{CM} \tag{73}$$

where CM is the processing capacity of the milling machine. The volume of yeast broth contained in one fermenter (FV_{SYB}) is adjusted to have the concentration of yeast in the fermenters reach $CY_{\text{SFM}}^{\text{goal}}$. The volume of fermentation liquor in one fermenter is given by:

$$FV_{\text{SFM}} = FV_{\text{SYB}} + FV_{\text{CJ}} \tag{74}$$

where $\boldsymbol{FV_{\text{SFM}}}$ is the volume of all liquor for SF taken in one tank. The yeast broth is produced in yeast culture tanks (SYT) in advance. Once the yeast is produced, it can be used many times through batch recycling until it spoils. The durability of the cultured yeast in the repeated-batch fermentation is defined as DY and, consequently, the total weight of the yeast (wet) over the season is represented as:

$$FA_{\text{SYB}}^{\text{s.yeast}} = \frac{OP}{DY} \cdot FC_{\text{SYB}}^{\text{s.yeast}} \tag{75}$$

where $C_{\text{SYB}}^{\text{s.yeast}}$ is the total weight of the yeast (wet) cultured in one cycle of yeast culturing and given by:

$$FC_{\text{SYB}}^{\text{s.yeast}} = N_{\text{SFM}} \cdot CY_{\text{SYB}}^{\text{targ}} \cdot FV_{\text{SYB}} \tag{76}$$

where $C_{\mathrm{SYB}}^{\mathrm{targ}}$ is the target concentration of yeast (wet) in the prepared yeast broth on a volume basis. Yeast culturing is implemented through three tanks of different sizes, as shown in Figure 3-16. The volume of the third tank is β times the size of the second one, which in turn is β times the size of the first one. The weight of yeast in one culture tank can be expressed as:

$$FC_{\mathrm{SYT}(3)}^{\mathrm{s.yeast}} = \frac{FC_{\mathrm{SYB}}^{\mathrm{s.yeast}}}{N_{\mathrm{SYT}(3)}} \tag{77}$$

$$FC_{\mathrm{SYT}(n)}^{\mathrm{s.yeast}} = \frac{N_{\mathrm{SYT}(n+1)} \cdot FC_{\mathrm{SYT}(n+1)}^{\mathrm{s.yeast}}}{\beta \cdot N_{\mathrm{SYT}(n)}},\ n=1,2 \tag{78}$$

The weight of yeast culture solution in a tank ($F_{\mathrm{SYT}(n)}$) is determined to have the yeast concentration reach $CY_{\mathrm{SYT}(n)}^{\mathrm{targ}}$. The yeast can be cultured by diluted molasses. In general, the molasses contains RS and sucrose. First, water and invertase are added to the molasses to hydrolyze sucrose into RS. Then, the yeast is cultured with the RS produced in addition to the RS that the culture originally contained. To produce the culture solution, water is added to the molasses until its brix concentration reaches 20%, and then yeast is cultured with some nutrients. As the concentration of yeast culture solution is not enough to be used for SF, some supernatant water is separated as waste water, such that the yeast concentration reaches $CY_{\mathrm{SYB}}^{\mathrm{goal}}$.

Electricity is consumed by fermenters, culture tanks, pump, cooling tower, and absorption chiller to produce chilled water in this process. The electricity demand of the SF process can be described as follows:

$$ed_{\mathrm{SF}} = ed_{\mathrm{SFM}} + ed_{\mathrm{SYT}} + ed_{\mathrm{PUMP}} + ed_{\mathrm{CLT}} + ed_{\mathrm{AbChill}} \tag{79}$$

where ed_m is the electricity demand of machine m.

Evaporation process

The clear juice is condensed through multiple-effects evaporators. The details of the evaporation process are shown in Figure 3-17. Once RS are converted into ethanol with SF, the concentration of ethanol in the inlet of the evaporation process should be less than 5% at the highest estimate. Then, most of the ethanol dissolved in the liquor would be evaporated as drain 1 with water because its boiling point (78° C) is lower than the inlet temperature. The existence of ethanol would slightly change the energy balance of the total multiple-effect evaporators. The ethanol in drain 1 can be recovered through the distillation and the dehydration process after being mixed with the diluted ethanol from molasses fermentation.

In this process, ethanol and some water are removed to achieve the goal of brix content for syrup (bxo_{sy}). In the Inv. process, the ethanol in clear juice is assumed to be completely evaporated in the first evaporator as drain 1 for its lower boiling point (78° C) and simplicity. The mass and energy balance in this process can be expressed as follows:

$$\sum_{i=1}^{N_{\mathrm{EVP}}} D_i = \left(1 - \frac{C_j^{\mathrm{bx}}}{ed_{\mathrm{SF}}}\right) \cdot F_j \quad , j=\text{I3 or ISin} \tag{80}$$

$$h_{\mathrm{steam}}(T_{\mathrm{LPS}}) \cdot D_s = h_{\mathrm{water}}\big(T_{\mathrm{EVP(1)}}\big) \cdot D_1^{\mathrm{water}} + h_{\mathrm{etoh}}\big(T_{\mathrm{EVP(1)}}\big) \cdot D_1^{\mathrm{EtOH}} + F_j \cdot c_j \cdot \big(T_{\mathrm{EVP(1)}} - T_j\big)$$

$$, j=\text{I3 or ISin} \tag{81}$$

$$\sum_i h_{\mathrm{steam}}^i \left(T_{\mathrm{EVP}(n-1)}\right) \cdot D_{n-1}^i = h_{\mathrm{water}} \cdot D_n + F_{\mathrm{I3}-(n-1)} \cdot c_{\mathrm{I3}-(n-1)} \cdot \left(T_{\mathrm{EVP}(n)} - T_{\mathrm{EVP}(n-1)}\right)$$

$$i=\text{water, etoh}, n=2,3,4,5 \tag{82}$$

$$U_1 \cdot A_1 \cdot \left(T_{\mathrm{LPS}} - T_{\mathrm{EVP(1)}}\right) = \Big(h_{\mathrm{steam}}\big(T_{\mathrm{EVP(1)}}\big) - h_{\mathrm{water}}\big(T_{\mathrm{EVP(1)}}\big)\Big) \cdot D_s \tag{83}$$

$$U_n \cdot A_n \cdot \left(T_{\mathrm{EVP}(n-1)} - T_{\mathrm{EVP}(n)}\right) = \sum_i \Big(h_{\mathrm{steam}}^i\big(T_{\mathrm{EVP}(n)}\big) - h_{\mathrm{water}}^i\big(T_{\mathrm{EVP}(n)}\big)\Big) \cdot D_{n-1}^i$$

$$, n=2,3,4,5 \tag{84}$$

where C_j^{bx} is the concentration of brix in stream *j*, D_s is the drain from LPS, D_i is the water drain from evaporator *i* after condensation through evaporator *i*+1, *DE* is the ethanol drain from evaporator 1 after condensation through evaporator 2, $h_{\mathrm{steam}}(T)$ and $h_{\mathrm{etoh}}(T)$ are the standard enthalpy of formation of water and ethanol per weight at temperature *T* respectively, c_j is the heat capacity of stream *j*, U_n is the overall heat transfer coefficient of the *n*-th evaporator, and A_n is the heat transfer area of *n*-th evaporator. In the Inv. process, drain 1 is supplied to the distillation column as stream ISd1. Although the presence of ethanol will cause azeotropy, which may have some unexpected effects on the energy balance, they are considered to be negligible considering the ethanol concentration. Instead of emission as drain 1, the stream ISd1 is mixed and distilled together with stream I6.

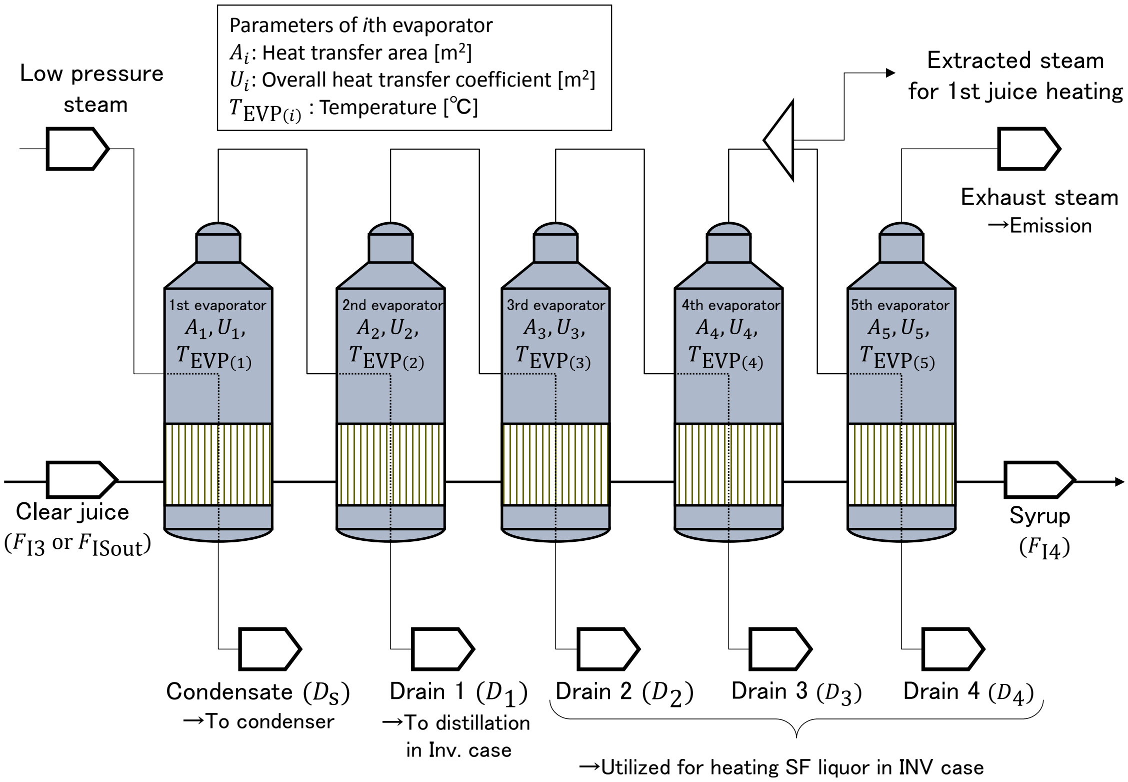


Figure 3-17 Diagram of the process and instruments of evaporation.

Crystallization process

Figure 3-18 shows the details of the crystallization process. The detailed information is described in Chapter 3.2.3. For every crystallization stage, the seed and mother liquor are fed to a crystallization pan first, water is added to dilute the feed to appropriate brix concentration, and then the feed is boiled at $F_{\mathrm{cr}(n)}$ [° C] under reduced pressure to reach the objective brix concentration (bxo_{sy}) while some water is added. LPS cascaded from HPSH is supplied as the heat source for boiling. Finally, the boiled product, called massecuite, is discharged to a crystallizer, and is separated after cooling into raw sugar and molasses with a centrifugal separator that uses electricity. This process accompanies the complex recycling of sugar and molasses.

As referred to in Ohara et al. (2012), SF contributes to the enhancement of sucrose purity in the Inv. process. Because this enhancement helps sucrose to be recovered in the crystallization process, the sucrose yield equation other than Eq. (41) should be applied in the Inv. case considering the difference in phenomena. In the extended model, the yield rate of raw sugar is given between the theoretical yield rate ($y_{\mathrm{MAX}}(Pur)$) and the yield rate in the Conv. process with the internal ratio ($p(Pur)$) as follows:

$$y_{n,\mathrm{Inv.}}(Pur) = p(Pur) \cdot y_{\mathrm{MAX}}(Pur) - \left(1 - p(Pur)\right) \cdot y_n(Pur),\ n\text{=1,2} \qquad (85)$$

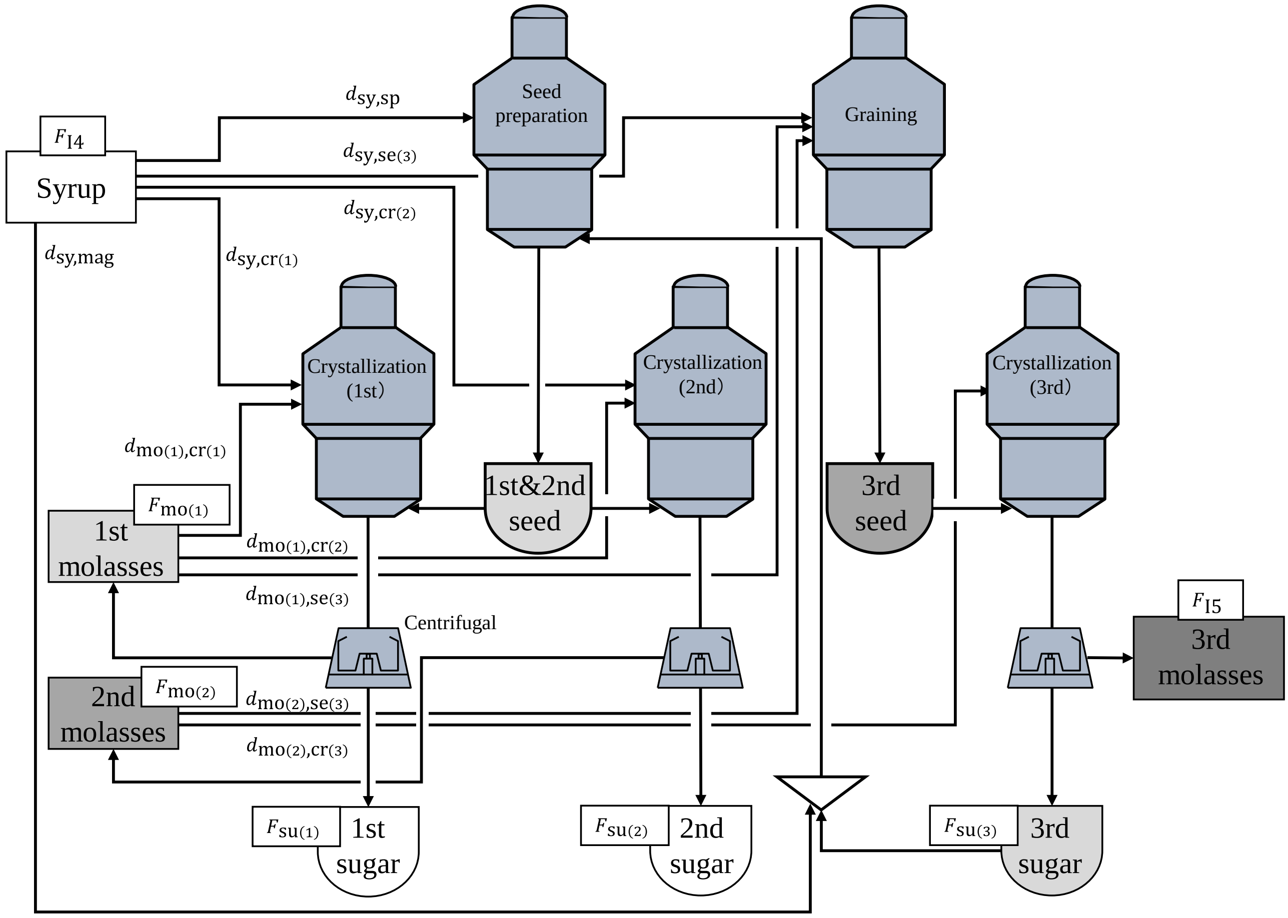


Figure 3-18 Diagram of the process and instruments used in crystallization.

The internal ratio represents the improvement effect of the sucrose yield brought by SF and depends on sucrose purity. On the assumption that it does not depend on the machine, it can be estimated by solving the following equation:

$$y_{n,\mathrm{Inv.,exp}}(Pur) = p(Pur) \cdot y_{\mathrm{MAX}}(Pur) - \left(1 - p(Pur)\right) \cdot y_{n,\mathrm{exp}}(Pur) \qquad (86)$$

where $y_{n,\mathrm{Inv,exp}}(pur)$ and $y_{n,\mathrm{exp}}(pur)$ are the experimental data on the yielding rate of raw sugar for Inv. and Conv. cases, respectively, under the same condition. The theoretical yielding rate should be also the function of sucrose purity and determined by the water content and the temperature of massecuite before centrifuge as follows:

$$y_{\mathrm{MAX}}(Pur) = 1 - \frac{(1 - C^{\mathrm{bx}}) \cdot S(T)}{C^{\mathrm{bx}} \cdot Pur} \qquad (87)$$

where $S(T)$ is the solubility of sucrose in water at temperature T and is given by:

$$S(T) = \frac{C_{\text{sat}}(T)}{100 - C_{\text{sat}}(T)} \quad (88)$$

where $C_{\text{sat}}(T)$ is the saturated concentration of sucrose, which is the function of temperature T as follows (Rein, 2007):

$$C_{\text{sat}}(T) = 64.4 + 0.0725T + 0.00206T^2 - 9.04 \cdot 10^{-6}T^3 \quad (89)$$

Eq. (85) is applied to the first and second crystallization in the Inv. cases, while the equation for the Conv. process (41) is applied to the third crystallization based on the assumption that the positive impacts of SF on the yield disappear in the third crystallization. One of the simulated results about the sucrose yield curves is shown in Figure 3-19. In this figure, we assumed that brix content (C^{bx}) is 95% and the temperature of massecuite before separation (T) is 40° C, and used the data (Ohara et al., 2012) to estimate $p(pur)$.

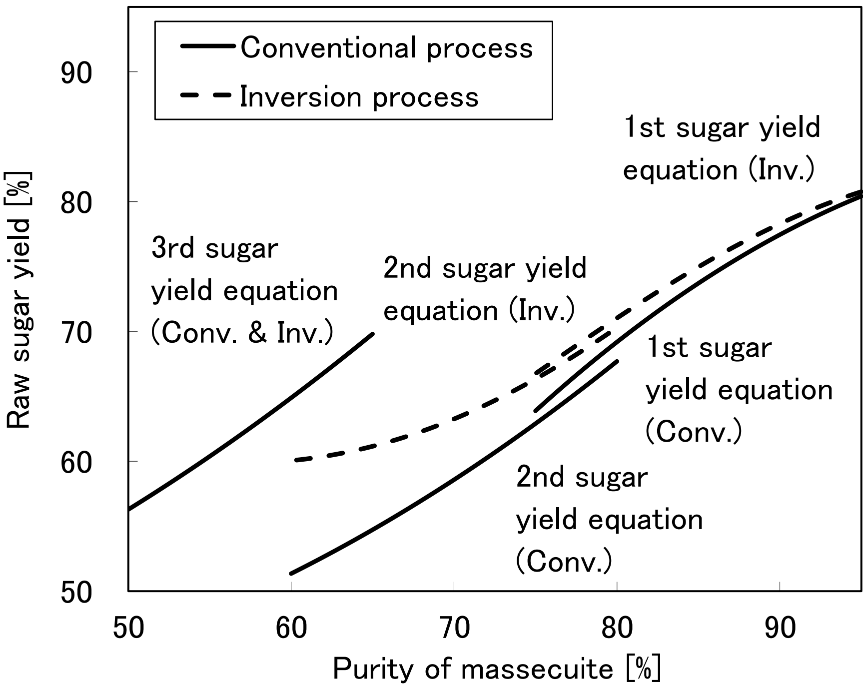


Figure 3-19 Raw sugar yield equations in the Conv. and Inv. processes.

3.3.3. Effects of Introducing Selective Fermentation on Productivity and Operability

To examine the applicability of SF to a mill that produces both raw sugar and anhydrous ethanol and its effect on the performance of the system, a case study was performed with the extended model.

Parameter settings and assumption. Five cases were prepared considering agricultural and industrial options as shown in Table 3-14. Case NiF-Conv.3 was the base case, where NiF8, which is one of the current major cultivars in the southwestern island of Japan for its high sucrose content and purity, is adopted by farmers and there was no change in the combined raw sugar and anhydrous ethanol production in the Conv. case. A high-yielding cultivar called KY01-2044 was adopted in other cases. This is a high-yielding cultivar developed for combined sugar and ethanol production, but is unpopular because of its fibrous and low sucrose content. For both cultivars, the Conv. and Inv. processes were considered. In addition to the three-boiling system, two-times crystallization was also considered for other cases for the feasibility of simplified operation on crystallization. In this case, a third crystallization was not conducted and, hence, the third sugar, which is the raw material of the first and second seed, was not produced. Instead, the first and second seeds were prepared only from graining syrup.

The basic information about the cropped sugarcane is based on actual data yielded in Tanegashima, which is one of the islands located at the northernmost end of the sugarcane farming regions in Japan. The data obtained are shown in Table 3-15. For nine samples, ff_{Sel} in Eq. (6) and f_{Sel}^{l} in Eq (5) were fitted so that $F_{\mathrm{A1(stem)}}$ and $C_{A1(\mathrm{stem})}^{i}$ match the data. The farmland area (Af) was set to 2,500 ha. The difference in yield and compositions among cropping types is not distinguished in this study. Agricultural equipment capacities, their fuel demand and input materials were set on the data investigated in Chapter 3.2.4.

Table 3-14 Parameter Settings of the Case Study

Case	NiF-Conv.3	NiF-Inv.3	KY-Conv.3	KY-Inv.3	KY-Inv.2
Cultivar	NiF8	NiF8	KY01-2044	KY01-2044	KY01-2044
Process	Conventional	Inversion	Conventional	Inversion	Inversion
Crystallization times	3	3	3	3	2

Table 3-15 Data Samples of Yield and Compositions of Sugarcane Used for the Case Study

	NiF8					KY01-2044				
	Yield	Sucrose	Fiber	Brix	Purity	Yield	Sucrose	Fiber	Brix	Purity
	t ha^{-1}	%	%	%	%	t ha^{-1}	%	%	%	%
No. 1	83.7	13.1	12.4	15.3	85.5	88.6	9.6	13.0	12.6	76.4
No. 2	78.1	14.3	9.3	16.0	89.2	107.0	11.5	15.0	13.5	85.1
No. 3	83.6	12.1	10.7	14.4	83.8	105.7	11.3	13.5	13.8	81.8
No. 4	53.8	9.6	10.4	12.2	79.0	65.3	8.9	13.7	11.8	75.7
No. 5	73.0	11.4	11.2	13.7	83.1	73.0	9.2	13.8	12.2	75.7
No. 6	75.4	11.6	11.1	13.8	84.2	75.1	7.6	13.3	10.3	73.8
No. 7	74.9	12.7	11.8	14.8	85.7	127.4	11.3	15.3	13.6	82.8
No. 8	45.3	9.0	10.7	12.0	75.0	101.6	9.0	13.2	12.0	74.9
No. 9	66.1	11.7	11.0	14.0	83.6	71.9	7.8	14.2	10.8	72.1
Average	70.4	11.7	11.0	14.0	83.2	90.6	9.6	13.9	12.3	77.6

The basic information about the cane sugar mill is also based on the actual mill on Tanegashima. The processing capacity of the mill (*CM*) was 1.5×10^3 ton d^{-1}. The ratio of maceration water to the cane weight (*mw*) was set as 0.3 kg kg^{-1}. During the juice heating process, cane juice was heated from 50 to 65° C ($T_{\mathrm{JH(1)}}$) through the first heat exchanger with extracted steam from multiple-effects evaporators, followed by the second heat exchanger where the juice was heated to 103° C ($T_{\mathrm{JH(2)}}$) with LPS. Before SF, the temperature of the steam IS1 was cooled from 95 ($T_{\mathrm{ip}}^{\mathrm{HEX3}}$) to 40°C ($T_{\mathrm{op}}^{\mathrm{HEX3}}$) at HEX3 by cooling water, and was then precooled from 40 ($T_{\mathrm{ip}}^{\mathrm{HEX1}}$) to 35°C ($T_{\mathrm{op}}^{\mathrm{HEX1}}$) at HEX1 by chilled water. The chilled water was supplied by absorption-chillers. After SF, the stream was heated at HEX4 with the drains from MEs (see Drain 2–4 in Figure 3-17) and, then, further heated to 95°C ($T_{\mathrm{op}}^{\mathrm{HEX2}}$) at HEX2 by cascaded LPS, which was at 140° C. The coefficients of performance of absorption and electric chillers were extracted from the average specification of existing facilities (Panasonic, 2016; Hitachi Metals, 2016) and set as 1.36 and 3.72, respectively. To prepare the yeast, phosphoric acid and ammonia solution were added to the culture as nutrients with antifoam agent. The amounts added are shown in Table A12. This yeast is repeatedly used in the fermenters, but discarded and produced anew every 30 days to avoid contamination. In addition, the yeast is sterilized once a week with sulfuric acid solution, which is neutralized with caustic soda after sterilization. In the crystallization process, seed and mother liquor are consumed at a ratio of 1 to 3 by weight, and magma is made by mixing syrup with the third sugar at a ratio of 1 to 3 by weight. The fixed parameters related to the distribution ratio of the syrup, first and second molasses are shown in Table A11and the others were determined uniquely because of the freedom degree of design bound by the total mass balance in the three-boiling system. In the case where there are only two crystallizations, the third crystallization is skipped and only syrup is used for graining. All the heat and electricity demand is covered by the cogeneration system in the mill. Bagasse is consumed as fuel and the surplus bagasse is stored. The parameters related to ethanol production is based on the case study in Chapter 3.2.4. More detailed information about the process parameters is shown in Tables A12 and A13.

These five cases were compared for the following points: productivity of the main and byproducts, operability of the crystallization process and economic feasibility. Raw sugar and anhydrous ethanol are the main products; surplus bagasse is also important for other purposes such as bedding or feed for neighboring livestock, or additional electricity sold to the grid. The yearly energy balance of the mill was also visualized to discuss the difference in productivity among the cases. These performance indicators were the direct output of the model.

To assess operability in the crystallization process, the ratio of the total working period of the crystallization pans (*TWC*) to that of the mill (*OP*: see Eq. (73)) was evaluated to analyze the busyness of crystallization pans scheduling. *TWC* was calculated from process inventory output from the model and required time for one batch is shown in Table A14.

Finally, the annual income of the mill and the capital investment for Inv. cases were compared in an economic evaluation. For a simple feasibility analysis, the return on investment (ROI) was evaluated by dividing the annual net income by the capital investment. The time value of money was not taken into account, and the interest rate was set to 0% for simplification. The method of calculating the annual income of the mill follows that in the case study in Chapter 3.2.4. Raw sugar can be sold at the market price in 2016 in Japan. The price of anhydrous ethanol per MJ is equal to gasoline, i.e., 67.2 JPY L^{-1}. The coproducts including bagasse ash, filter cake and vinasse are sold at the price of the fertilizer they replace on a nitrogen, phosphorus and potassium content basis. The mill purchases sugarcane at a price per weight that is determined based on current Japanese policy, where it linearly correlates with the measured sucrose content. The price of the other input material is from the literature (The Chemical Daily, 2015). The number of employers and their labor cost were set as 59 and 1.22×10^4 JPY $person^{-1}\ d^{-1}$.

The calculation of the total initial cost for SF was based on Guthrie's cost estimation method (Guthrie, 1969) as follows:

$$\text{Total initial cost} = \sum_m BC_m \cdot (MPF_m + MF_m - 1) \quad (90)$$

where BC_m is the base cost, MPF_m is the material and pressure correction factors, and MF_m is the module factor for machine m. In this case study, four S&T HEXs, a cooling tower, an absorption chiller, three fermenters, and five culture tanks (one first, two second, and two third yeast culture tanks in Figure 3-16 were considered to be new equipment.

The initial costs for heat exchangers and other facilities were derived as functions of representative parameters, e.g., heat-transfer area or cooling duty, which are summarized in Figures A1-A3 (Saito, 2000; Obana, 2011). The summation of these indicates the required investment for the heat exchanger network to implement selective fermentation. Note that the cost functions shown in the figures exclude the connecting pipes, pumps, electric construction, piping construction and basic construction for users of utilities. Although an additional cost for maintenance because of the high operating ratio of the boiler or other facilities would be generated, no additional cost was considered in this study.

The base cost of the fermenters and culturing tanks are estimated as follows:

$$BC_{\text{tank}} = a \cdot FV^b + c \quad (91)$$

where the values of a, b and c are shown in
Table A15. The volume of the fermenters and second and third culturing tanks was estimated to be

100% larger than the volume taken in them. The volume of the first culturing tanks was estimated to be 50% larger than the volume taken in them. The MPF_m for all of the equipment above was 1.00 and MF_m was set as 2.95 (typical value). The cost information on equipment is based on a publication (Saito, 2000).

Simulation results. Figure 3-20 shows the results of raw sugar and anhydrous ethanol production. The plots are the mean value derived from nine samples while the error bars represent the 95% confidence intervals of means. There is no significant difference between the five cases for raw sugar production as their error bars widely overlap, although the mean value in KY-Inv.3 is higher than the base case. Ethanol productions in KY-Conv.3 and KY-Inv.2 are remarkably high, while that in NiF-Conv.3 is not at the cost of an increase in sugar production; KY-Inv.3 is also higher than the base case although half of their confidence intervals overlap. Looking at the whole plots, the pareto-optimal set of raw sugar and anhydrous ethanol production can be achieved when KY01-2044 is chosen. If the Inv. process is adopted without changing the cultivar, the amount of ethanol produced will decrease instead of increasing in raw sugar. However, both productions can be improved from the base case if the cultivar is changed to KY01-2044.

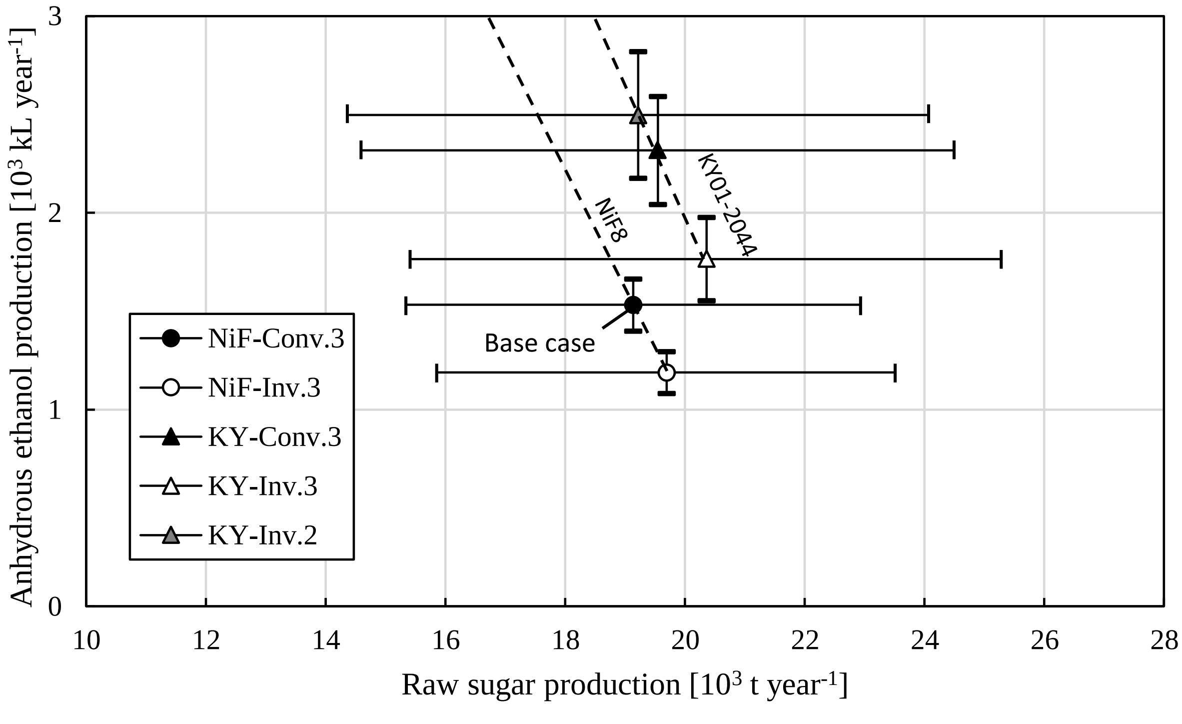


Figure 3-20 Raw sugar and anhydrous ethanol production with error bars.

Figure 3-21 shows the detail of the energy balance that was calculated in the mill throughout the year from the average sample shown in Table 3-15. The height of the bar graph on the positive side stands for the energy equivalent to generated bagasse and that on the negative side stands for the energy consumption of the mill throughout the year. The plots represent the summation of the positive and the negative heights, and, hence, the energy equivalent to surplus or shortage of bagasse in the mill. The shortage is supplemented with fuel oil A.

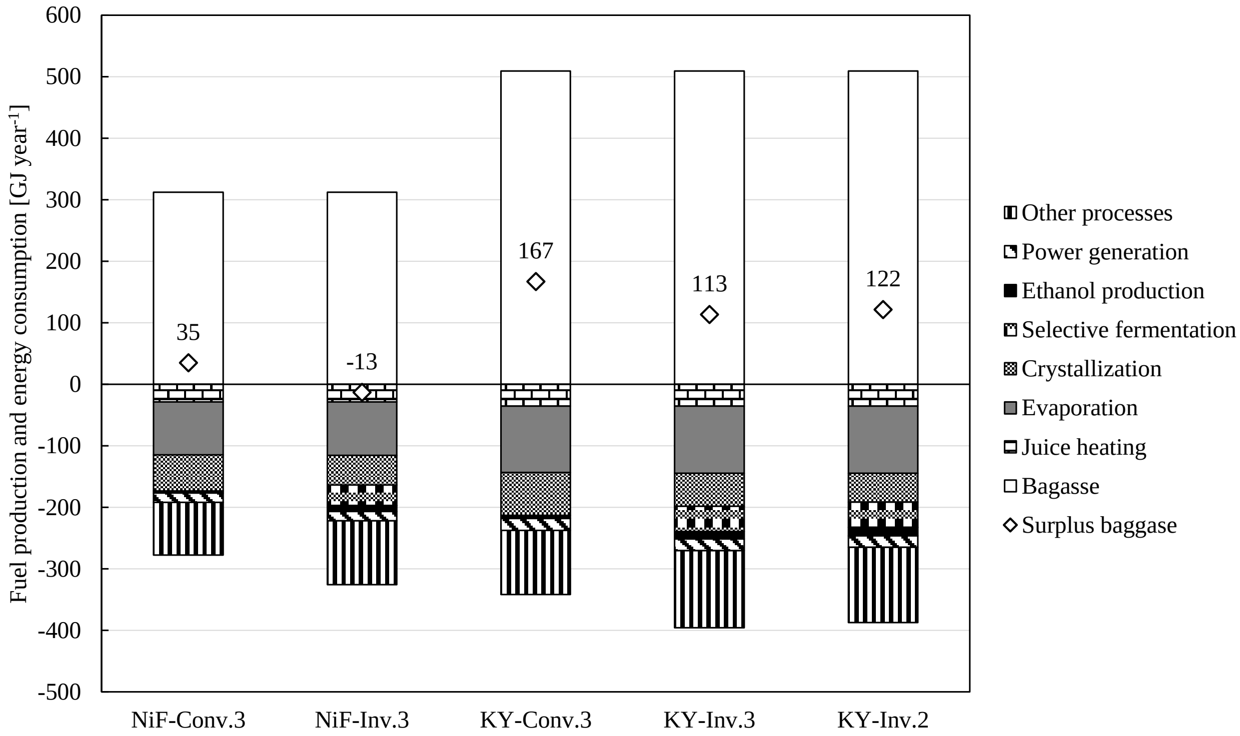
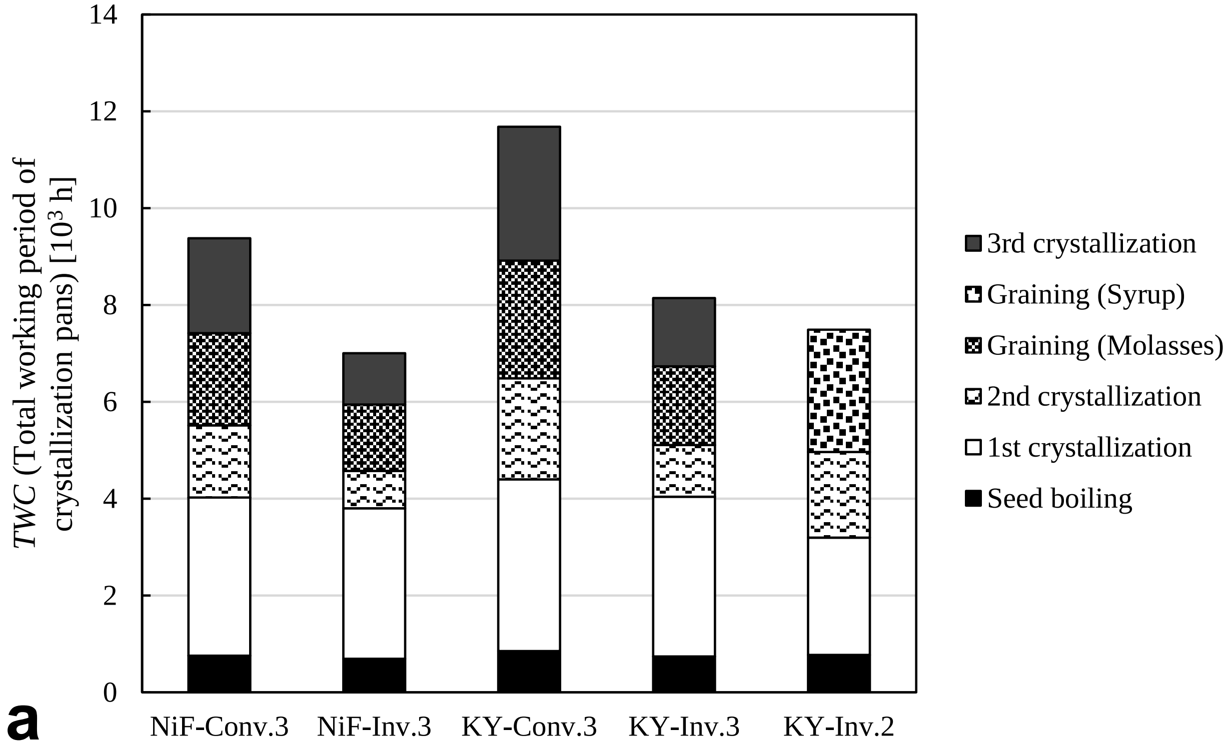


Figure 3-21 Detail of energy balance in the mill. Bagasse on the positive side represents available energy if all generated bagasse is combusted. The negative side represents energy consumption. The plots of "Surplus bagasse" represent the summation of positive and negative sides.

KY01-2044 produces more surplus bagasse than NiF8 as also can be confirmed in Figure 3-9 in Chapter 3.2.4. For all cases, surplus bagasse is generated except for NiF-Inv.3. As can be seen from the first four cases, the Inv. cases consume more energy than the Conv. cases. The energy consumption of ethanol production also increases in the Inv. cases because larger amounts of water in the fermented broth must be distilled because it receives the diluted ethanol-containing drain from evaporator 1. These consumption figures give rise to bagasse shortage in the case of NiF-Inv.3, but this does not apply to the cases where KY01-2044 is chosen. This is because in those cases there is abundant surplus bagasse. Regarding the breakdown of energy consumption, the evaporation process is the most dominant and the crystallization process is the second for all cases. Although SF helps to reduce the energy consumption in the crystallization process, the energy demand in SF cancels this advantage. Two-times crystallization also saves consumption in the crystallization process, its contribution to the total is relatively low.



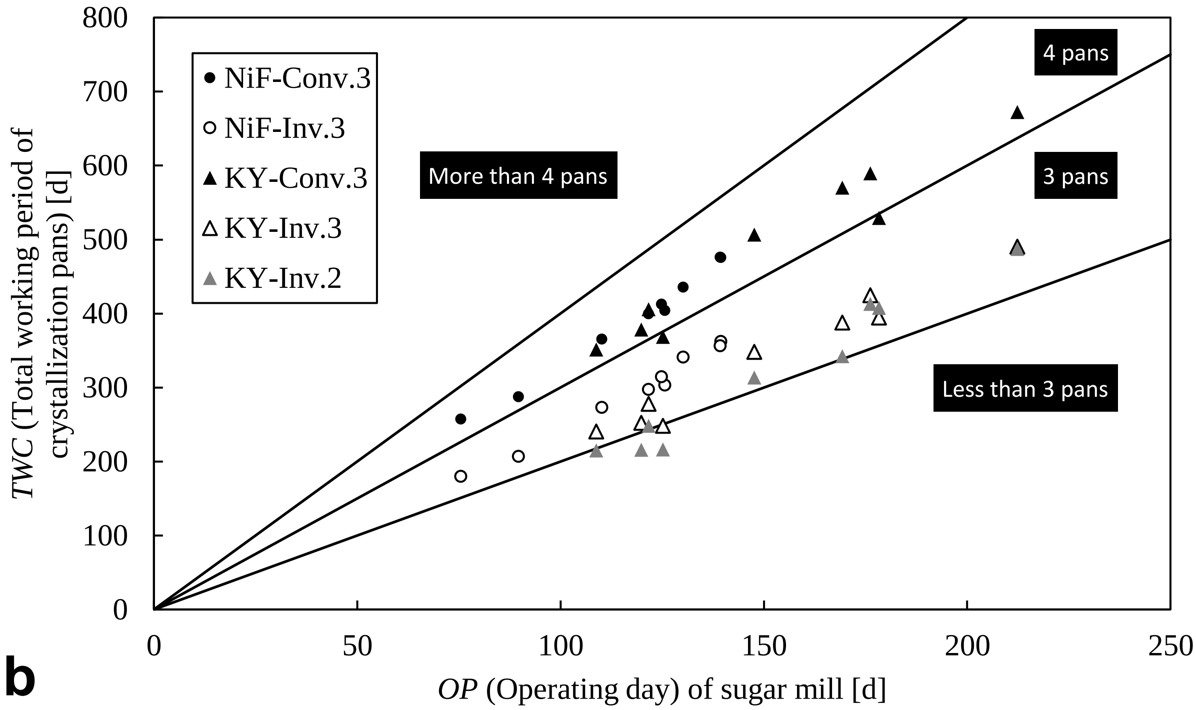


Figure 3-22 (a) Total working period of crystallization pans (TWC) and their time distribution for an average sample. (b) Operating days of the sugar mill (OP) and total working period of crystallization pans (TWC) for all nine samples. The area is divided into four fields according to the number of required crystallization pans.

Figure 3-22a compares the breakdown of the total working period of crystallization pans (*TWC*) for the average sample. For the first four cases adopting a three-boiling system, graining by molasses, the first and third crystallizations are dominant. It takes more time for KY-Conv.3 than for NiF-Conv.3 to complete each operation. In the Inv. cases, the time for the second and third crystallization, and graining could be reduced because a larger amount of raw sugar can be extracted at the first crystallization, resulting in the reduction of the molasses that has to be boiled again. In the KY-Inv.2 case, the total crystallization time could be shorter, although there is almost no difference in sugar yield from NiF-Conv.3 (see Figure 3-20). This case requires time for graining from syrup and the second crystallization, but it skips the third crystallization and graining from molasses.

Figure 3-22b maps the *OP* and *TWC* for nine samples and for each case. The minimum numbers of required pans are also shown as lines. On this graph, the left-upper area represents busy scheduling of the crystallization pans, because operators have to spend much time handling crystallization pans in a short period. In the Conv. cases, even if the cultivar is changed from NiF8 to KY01-2044, the busyness of the crystallization pans does not change, but their total working period is just extended. This result implies that although the syrup from KY01-2044 requires more time per weight to finish crystallization, this disadvantage is mitigated because the syrup feed per time is slower due to it being more fibrous than that from NiF8. SF helps reduce the total crystallization time for both cultivars thanks to the improvement in crystallization efficiency. Moreover, two-times crystallization can also further shorten the time. Given that four crystallization pans are currently used in the base case, the three Inv. cases make it possible for the operators to secure time for every batch or to reduce the number of crystallization pans to three. Note that, in general, it takes longer to crystallize as the sucrose purity decreases, but in this study all crystallization time per batch is assumed to be the same regardless of the purity for each operation (see Table A14). Therefore, in reality, there would be a tendency for crystallization to take longer than the simulation results if the sucrose purity of the sugarcane is lower.

Figure 3-23 shows the details of annual profit, cost and income for the mill for the average sample. The sales of raw sugar dominate the entire gains in all cases, followed by sales of anhydrous ethanol and coproducts. Regarding the total profit, there is a tendency that higher raw sugar production results in higher profit unless the cultivar is not changed. This means that raw sugar production is more profitable than anhydrous ethanol under the current price settings. The negative side for cost is that the purchase of sugarcane accounts for a large portion in all cases, followed by expenses for transport of sugarcane and labor.

The rank of total income reflects the amount of raw sugar production except for NiF-Inv.3. As can be seen in Figure 3-21, not enough bagasse is generated to supply all the energy demand in this case because of the low content of fiber and energy consumption in SF, and, therefore, additional fuel is required to supplement the shortage as also can be confirmed in the NiF-Inv.3 case in Figure 3-23.

If KY01-2044 is chosen, the Inv. process contributes to the increase in income because raw sugar production can be enhanced without consuming fuel oil A. Note that these rankings may change depending on the price of raw sugar and anhydrous ethanol.

Figure 3-24 shows the result of sensitivity analysis of ROI to the variation of feedstock. R_RO is the ratio of RS to the summation of RS and other brix. Among feedstocks having the same sucrose purity, the one with high R_RO has a high probability of introducing SF easily. In this sensitivity analysis, R_RO is chosen as 25% and 75%, the purity is chosen as 80% and 70%, and the unit yield is operated from 50 to 150 t ha^{-1}. The results for NiF-Conv.3 and KY-Inv.3 are also plotted in the figure. The ROI of KY-Inv.3 case was 5.2%, which indicates that the case is not feasible if the payout time is set as 7 years. ROI increases constantly along the unit yield. If the unit yield reaches 103 t ha^{-1} for 80% purity and 0.25 R_RO, ROI exceeds 25%, which is feasible with a high probability. Furthermore, if R_RO is 0.75, 25% of ROI can be achieved more easily. Even if the purity is 70%, there still remains some feasibility; 114 t ha^{-1} and 0.25 in R_RO will result in 25% in ROI. Some high-yielding cultivars that have 177.2 t ha^{-1} for 74.2% purity in U.S.A (Bischoff et al., 2008), and 128.0 t ha^{-1} for 79.2% purity in Australia (Jackson et al., 2010) have been reported. If similar cultivars can be found in Japan, it would be rather realistic to introduce SF with a shorter payback time.

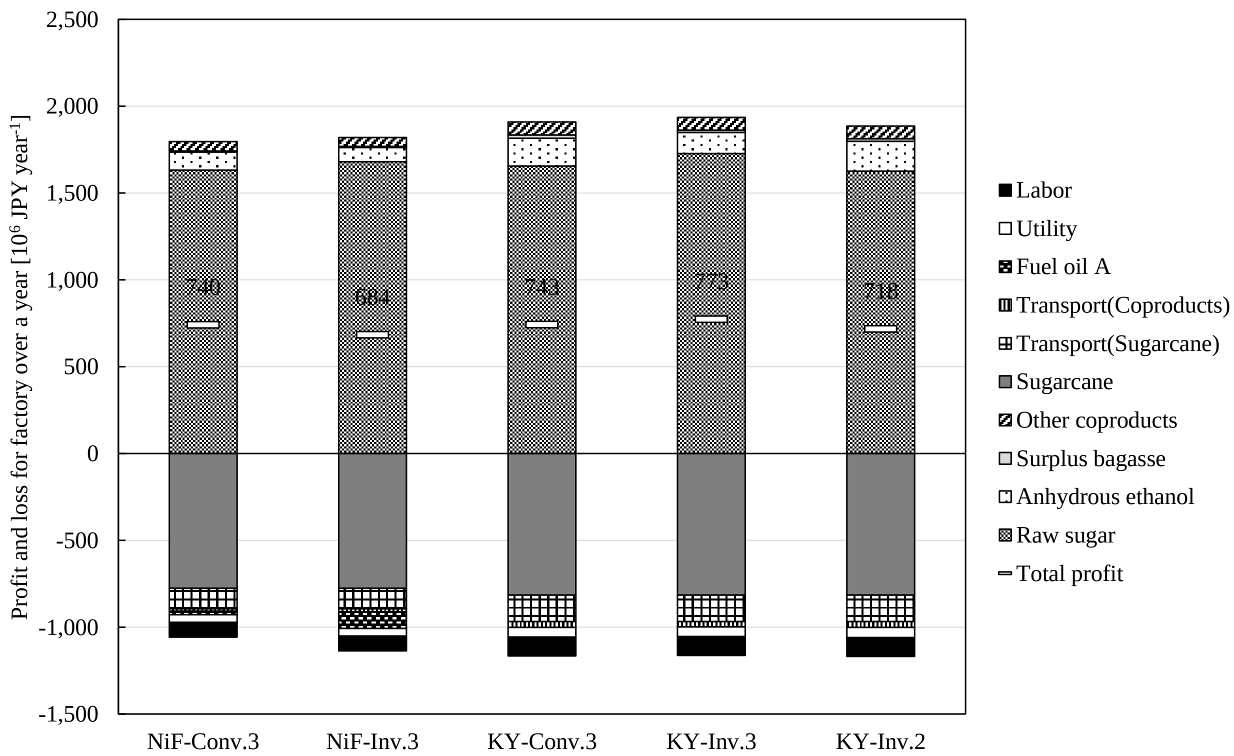


Figure 3-23 Annual profit, loss and total income of the mill. The positive side represents profit and the negative side represents loss. The "Total profit" bars are a summation of the positive and negative sides. Depreciation for capital investment of SF was not considered in Inv. cases.

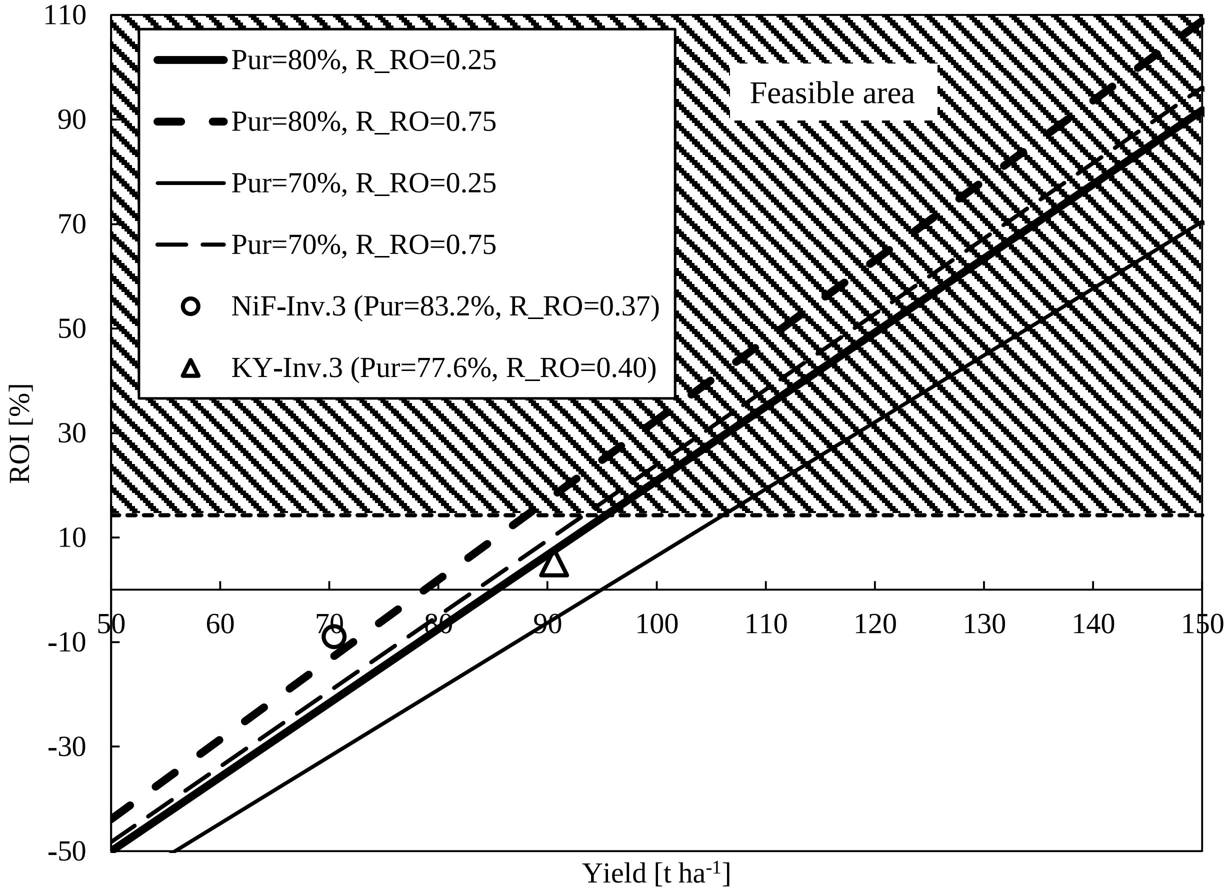


Figure 3-24 Sensitivity analysis of yield and RS content to ROI. R_RO is the ratio of RS to the summation of RS and other brix. The area where capital investment for the Inv. process is feasible if payout time is set as 7 years is shown as a slashed line.

3.3.4. Discussion

The results of the case study presented above indicate that the Inv. process enables cultivars that have been regarded as impractical for their low sucrose purity to become effective for combined production. High-yielding cultivars such as KY01-2044 have not been favored by the Japanese sugarcane industry and farmers because of their low sucrose purity, which depresses the raw sugar yield and prolongs the crystallization operations. However, SF can overcome those drawbacks; it improves raw sugar yield as well as the operability in the crystallization process (see Figure 3-20 and Figure 3-22a). While SF consumes some energy, additional fuel oil A consumption can be avoided if cultivars like KY01-2044 that contain high fiber and, consequently, produce abundant bagasse are chosen as feedstock (see Figure 3-21).

The mills where SF was installed had another advantage in their flexibility because choosing the Inv. process is optional and, hence, they can widely adjust the production balance of raw sugar and ethanol. Raw sugar is an indispensable food for human beings, but its supply is not stable because of fluctuation in the yield and compositions of the crops, which depend on month, year and area (OECD and FAO, 2014; ALIC, 2017a). The market price is also exposed to uncertainties that originate from the international situation (OECD and FAO, 2014; ALIC, 2017b). Once SF is installed, operators can choose better processes from the Conv. and Inv. processes that consider crop conditions and the market demand.

This advantage is meaningful for mitigating problems caused by prolonging the operation days of mills when high-yielding cultivars are chosen. While the long-operation period is helpful for farmers because they can avoid the labor-intensive season for harvesting, it causes a temporal discrepancy between the maturity of the crops and the required time for processing in the mill. In Japan, the ripening period of sugarcane is December to February, whereas the working period of the mill could be between 109 to 212 days (see Figure 3-22b). As the ratooning treatment must be finished before April for the next cropping, the mill has to start working from October in the worst-case scenario. In general, immature crops in the early season contain much RS (Qudsieh et al., 2001; Solomon, 2009) and, consequently, reduce the efficiency of raw sugar production in the mill. This drawback, however, can be overcome to some extent if SF is installed, because operators can choose the Inv. process to avoid the drop of raw sugar yield in the season when the content of RS in the feedstock is high enough to interfere with operability in the crystallization process. Moreover, mixed adoption with early-ripening cultivars that have been recently developed, can be one of the solutions for maintaining the sugar production (KARC, 2013). A dynamic simulation considering the relationship between the harvest season of sugarcane and its maturity should be performed for a detailed evaluation.

The SF brings those benefits, but the low level of economic feasibility (see Figures 3−23 and 3−24) is a major concern. Although the capital investment of SF cannot be expected to be saved, there are possibilities of reducing cost on existing equipment or increasing yield of raw sugar that were not considered in the case study. According to Figure 3-22b, the simplified operations in the crystallization process with SF have a potential of changing the concept of process design and operations by reducing the number of crystallization pans, or spending more time on one batch for boiling to exploit raw sugar. An additional gain from selling surplus electricity to the grid by combusting all generated bagasse is also one of the solutions for improving profitability. The selling of electricity has been already implemented in some mills in Brazil, but no mill sells electricity in Japan because it is impractical to sell electricity only in the limited season of around 4–6 months. One of the solutions would be year-round electricity production by collecting local renewable resources such as wood residues for fueling the boiler in the off-season (Kikuchi et al., 2016b). In this case, high-yielding cultivars such as KY01-2044 are advantageous because they can produce far larger amounts of surplus bagasse than NiF8 (see Figure 3-21). To obtain more electricity, it may be also useful to change the power conversion turbine from a back-pressure to a condensing turbine that has a higher conversion efficiency.

One of the remaining issues is that it is not easy to shift from the current system to the proposed one even if all of the abovementioned problems are solved because multiple decision makers including farmers and sugar mills should be involved in this transformation. In this study, all parameters were assumed as variable from the perspective of the researchers, but, in reality, the question of who is responsible for each parameter should be carefully discussed. For example, cultivars are determined by farmers. In Japan, it is not easy for them to change to high-yielding cultivars because they cannot make as much profit as from high-sucrose cultivars under the policy that the price is related to the sucrose content. Political support could be a key solution for motivating farmers to choose a high-yielding cultivar. Because RS and fiber, as well as sucrose, could contribute to the final benefit thanks to SF, all of those components should determine the value. Exergy-based cost determination proposed by Pellegrini and Oliveira Jr (2011) may be one of the solutions to evaluate sugarcane as the feedstock for combined multiple production appropriately.

As a future strategy for improving the economic feasibility of SF or further enhancing the productivity of mills, a new guideline for plant breeding is desired as discussed in Figure 3-24. To date, promising cultivars that have excellent multiple characteristics, such as high sucrose purity, high unit yield, and high resistance toward insects and diseases, have been sought through plant breeding. However, breeding gradually approaches its limitations. It is becoming difficult to find a new cultivar every year. At this point, SF lessens the significance of sucrose purity. As a result, it lowers the hurdle for finding new cultivars that have good characteristics except for sucrose purity. In other words, this change in the requirement on crops will contribute to an enhanced and stable production of raw sugar and anhydrous ethanol if new cultivars are developed toward this new requirement in the future. In addition, if more kinds of cultivar are available, it would lead to the diversification of cultivars. This situation is desirable from a resilience point of view because it reduces the risk of being totally ruined because of environmental disturbances (Lin, 2011).

Through the above discussions, it can be stated that a simulation-based analysis using limited experimental data and existing models could assist the transformation of farming and sugar milling by identifying desirable and feasible alternatives with SF in the design stages. The advantages of not only high-yielding cultivars but also SF have not been accepted, as Figure 3-23 quantitatively supports. However, the simulation-based analysis conducted in this thesis raises awareness of new alternatives when both cultivars and SF are introduced simultaneously that might not have been recognized. To validate the simulation results from the developed model, it is necessary to get actual data from the plant after SF is installed. The extrapolation from actual data after constructing the equipment has great potential for the estimation of process data required for evaluating the system performance with lower uncertainties.

3.4. Alternative Generation by Picking up External Requests

The method developed in Chapter 3.2 makes it possible to generate a larger number of alternatives than ever before. It means plant-derived production may potentially meet an external request that has been turned down. A case study on Japanese sugarcane industry in this section verifies the potential of generating alternatives to meet such request using the model extended from the one in Chapter 3.2.

3.4.1. Potential External Request from Peripheral Region

In Japan, all cane sugar mills are on remote islands that are located south of the southernmost tip of Kyushu Island. The power systems in these regions are in the form of microgrids that are isolated from each other: The scales of the power demand in these areas are from 0.1 to 96.9 MW (Kikuchi et al., 2016c). In general, these remote islands are at a disadvantage in the thermal power generation cost because of their coastal transportation cost from an oil refinery. For example, the price of gasoline in Okinawa Prefecture is 9.2 yen L^{-1} higher than that in Japanese average (ANRE, 2017).

To avoid the high dependence on fossil fuels, the construction of biomass power plants has been planned recently (erex Co., Ltd., 2017), although the energy security remains uncertain because their biomass feedstock is palm kernel shell imported from other countries. While photovoltaic and wind powers are strong candidates for these regions, it is difficult to control their output as we want because of their dependence on weather conditions. Therefore, other power plants for adjusting the fluctuations in power supply and demand. With regards to the islands that are rich in well-managed forest, combined heat and power system utilizing woody biomass should be another candidate to ensure the energy security (Kanematsu et al., 2017b). However, not all these remote islands are rich in woody resources.

As referred in Chapter 2.1.1, bagasse can be another source for power generation. It cogenerates with raw sugar at sugar mills and, therefore, requires no cost for collecting them. In addition, all these sugar mills have a power plant for sugar production. The business of retrofitting the power plant to sell excess electricity to the grid has been reported in other countries such as Philippines (METI, Japan, 2014), Thailand (KANSO Co., Ltd., 2005), Vietnam (JCM, 2014), Cuba (JICA et al., 2016), and India (NIPPON KOEI Co., Ltd., 2012). However, there are two challenges for the Japanese sugar mills to implement selling electricity. First, the shortness of the current working period limits the potential of selling electricity. In Japan, the working period of sugar mills is around four months a year. Second, there is not economic incentive enough for the mills to sell electricity considering the amount of the surplus bagasse. Its amount is 10-20% of all the bagasse generated. In addition, the mills run out of bagasse depending on the year. In this case, the shortage is covered with fuel oil A. Alternative candidates that enable the extension of the working period, saving the energy consumption and increase in bagasse generation are desired.

Cultivar changes to high yielding cultivars such as KY01-2044 (see Chapter 3.2.3 or Table 3-2) could be a solution to overcome this. As Ohara et al., (2009) reported and Table 3-12, Figure 3-8, and Figure 3-9 indicate, high yielding cultivars have a potential of increasing bioethanol and bagasse production without decreasing raw sugar production. Moreover, the working period can be extended as Figure 3-22b shows because of its large processing amount. These outcomes could dispel the above concerns.

This transition would involve a retrofitting design of the power plant in the mills because the current energy flows in the mills have been designed to maximize the benefit from only raw sugar production: Steam and electricity required for raw sugar production are provided from the boiler and the power plant. As described in Chapter 3.2.3, steam is consumed for the milling, clarification, evaporation, and crystallization processes as well as power conversion with the steam turbine. On the other hand, electricity is just consumed for conveyers and instrumentation equipment. The current energy flow has been designed with BPST (see Chapter 2.1.1) considering the thermo-electric ratio of the mills that is relatively lower compared to the conversion efficiency of the usual steam turbine power plant. In addition, the sugar mills emit a considerable amount of waste heat because of its rough heat integration (Kikuchi et al., 2016b). Simultaneous change of sugarcane cultivar and the design of the power plant may enhance the potential of selling electricity.

In this section, an implementation analysis of bagasse power plants interconnected with the main grid of the island was conducted considering the technology options on sugarcane cultivar and the power plants in sugar mills. As a target region, Okinawa Main Island, Izena Island, Kume Island, Minami-Daito Island, Kita-Daito Island, Miyako Island and Ishigaki Island are chosen. A simulator that can estimate the mass and energy balance of a cane sugar mill for the type of the cultivar and power plant is developed based on SugaNol developed in Chapter 3.2 and 3.3. Using the developed simulator, three cases are prepared and compared in terms of the amount of raw sugar, molasses and bagasse produced, the energy balance in the period of sugar production, the potential of electricity sold and the maximum ratio of substitution of power generation from fossil fuels to bagasse.

3.4.2. Model Extension for Simulation Considering Electricity Selling

The replacements of sugarcane cultivar and the type of the steam turbine in the sugar mill are considered as options in this study. The cultivar is one of the elements that influence the characteristics of harvested sugarcane such as a unit yield per farmland area and compositions, which may affect both electricity and raw sugar yields. The period of sugar production depends on the unit yield and the milling capacity of the sugar mill. Cultivars with higher fiber content will produce larger amount of bagasse and may, hence, increase the power generation output, while ones with lower sucrose content will result in a decrease in raw sugar production. With regard to the steam turbine, two types are considered as available options based on sugar mills that sell electric power (Bouda, 2004): Back-pressure steam turbine (BPST) that is suitable for providing one kind of steam and chosen by all of the sugar mills in Japan, and condensing-extraction steam turbine (CEST) that is adopted where two kinds of steam are required. This choice will influence the provision balance between the steam and electricity (Rein, 2007) without affecting the raw sugar yield. If electricity is sold with CEST during no-crushing season, steam for operating roll mills (RMs) in the sugar production season can be used for generating electricity.

Implementation analysis of bagasse power plant requires the mass and energy balance for the combinations of conditions including the options above. The process model "SugaNol," developed in Chapter 3.2, is extended to estimate them in this section. As this model targeted only the current energy flow in Japanese mills, where BPST is chosen, it cannot simulate the energy flow for CEST. In this case, the size of CEST have to be also estimated based on the feed rate of bagasse and steam demand from sugar production. To meet these requirements, a module for analyzing energy balance for both BPST and CEST is incorporated as follows.

Figure 3-25a shows the energy flow if BPST is chosen (Kikuchi et al., 2016b). Main steam from boiler passes through a high-pressure steam header (HPSH) as high pressure steam (HPS) and, then, is distributed to RMs, BPST, and pressure reducing valves (PRVs) if needed. The steam exhausted in RMs and BPST and the pressure-reduced steam from PRVs go through low-pressure steam header (LPSH) as low pressure steam (LPS), followed by exhaustion in the evaporation, crystallization and other processes. If the LPS demand is larger than the provision from RMs and BPST, the shortage is compensated for via PRVs. If the LPS demand is smaller than the provision, surplus LPS is generated. More details of the energy flow is described in Chapter 3.2.3. The scale of electricity sold E_{sell} [kW] can be described as follows:

$$E_{\mathrm{sell}} = E_{\mathrm{Max}} - E_{\mathrm{cons}} \tag{92}$$

where E_{Max} [kW] is the rated power output of the current sugar mill, and E_{cons} is the electricity demand of the sugar mill. HPS is provided for BPST so that the scale of the total power generation reaches E_{Max}.

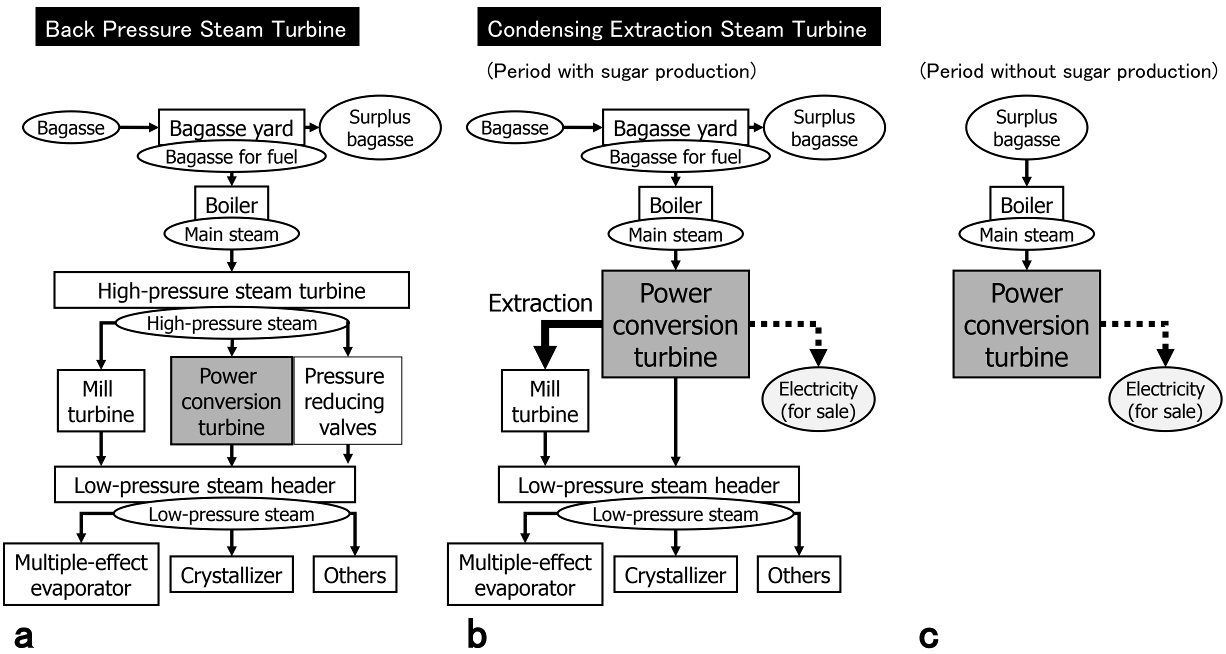


Figure 3-25 Current and proposed energy flow in Japanese cane sugar mills. (a) BPST case in the period with sugar production, (b) CEST case in the period with sugar production, (c) CEST case in the period without sugar production.

Figure 3-25b shows the energy flow for if CEST is chosen in the sugar production period. All of the main steam is fed to the inlet of CEST and exhausted steam is used for some processes as is BPST case. In general, both the pressure and temperature of the main steam for CEST is higher than those for BPST and the steam required for RMs is extracted from the middle stage of CEST. Analysis of energy balance in this case requires a module that can estimate power generation output based on the pressure, temperature and flow rate of the main steam and extracted steam for RMs. A module developed by Konishi (2010) can meet these requirements. In this module, the modeled CEST is composed of the first turbine and the second turbine, the types of which are back-pressure steam one and extraction steam one, respectively. The required steam can be extracted from the connected point between the two turbines. Electricity for selling is calculated by solving the following equations:

$$E_{\mathrm{sell}} = E_1 + E_2 - E_{\mathrm{cons}} \tag{93}$$

$$w_1 = w_2 + w_{\mathrm{RM}} \tag{94}$$

$$E_i = \left(h(T_{i-\mathrm{in}}, P_{i-\mathrm{in}}, -) - h(T_{i-\mathrm{out}}, P_{i-\mathrm{out}}, -)\right) \cdot w_i \tag{95}$$

$$E_i = \left(h(T_{i-\mathrm{in}}, P_{i-\mathrm{in}}, -) - h(-, P_{i-\mathrm{out}}, S_{i-\mathrm{in}})\right) \cdot ie_i \cdot w_i \tag{96}$$

where E_i [kW] is the generated electric power in *i*-th turbine, w_i [kg s^{-1}] is the flow rate of steam passing through *i*-th turbine, w_{RM} [kg s^{-1}] is the flow rate of the steam extracted from RMs, $h(T, P, S)$ [kJ kg^{-1}] is the specific entropy of steam that is determined by two of T (temperature), P (pressure) and

S (entropy), and ie_i is the internal efficiency of i-th turbine.

Figure 3-25c shows the energy flow for if CEST is chosen in the season after sugar production period. To calculate the scale of electric power generation, an existing estimation equation based on actual data of power plant with steam turbine (Kikuchi et al., 2016a) was applied as follows:

$$\eta = (2.672\ln(E_{\mathrm{sell}}) - 4.128) \cdot 10^{-2} \quad (97)$$

where η is power conversion efficiency and PB [kW] is the thermal power from b s agasse combustion per time. E_{sell} and η can be calculated by solving Eqs.(97) and (98) simulateously.

$$E_{\mathrm{sell}} = \eta \cdot PB \quad (98)$$

3.4.3. Implementation Analysis of Bagasse Power Plant on Regional Power System

Case settings

Three data sets of options shown in Table 3-16 were prepared as alternatives for each cane sugar mill. In Case A, surplus electricity is sold at the current rated power output using the standard cultivar in the area and the current power plant only in the period of sugar production. Surplus bagasse that cannot be consumed in this period is disposed of in this case. In Cases B1 and B2, a high-yielding cultivar "KY01-2044" is chosen, BPST that is used to generate electricity is replaced by CEST, and surplus electricity is sold. Electricity is sold only in the period of sugar production consuming all generated bagasse in Case B1, whereas, in Case B2, electricity is sold both during sugar production and also at other times with minimum provision of steam for the mill and storing surplus bagasse in the sugar production period. In both Cases B1 and B2, the size of CEST is determined so that the scale of electrical power generation keeps 80% of the rated power output during sugar production season. The power output after finishing sugar production in Case B2 is determined to 50% of the rated power output in reference to an existing report about the minimum-output ratio in thermal power generation (OCCTO, 2017). In this period, electricity is continuously sold until the surplus bagasse is exhausted. In cases where there are multiple sugar mills in an island, all the mills start sugar production on the same day. The inlet and outlet temperature and pressure of the steam turbine were based on the literature(Kikuchi et al., 2016b; Macedo et al., 2008).

As evaluation indicators for the ability of a sugar mill to sell electricity, the annual amount [kWh] and the scale [kW] of electricity sold, and the length of the period [day] for the selling were chosen. Electricity from bagasse has a potential of partly replacing that from fossil fuels. To assess this potential, the substitution ratio of power generation from fossil fuels to bagasse (*SR*) was defined based on the above indicators and the power supply configuration for each island shown in Table 3-17 as follows:

$$SR = \frac{\sum_m \int_0^Y E_{\mathrm{sell}}(t,m)\mathrm{d}t}{E_{\mathrm{fos}} \cdot Y} \tag{99}$$

where $E_{\mathrm{sell}}(t,m)$ is the scale of the electricity sold from sugar mill m at time t, Y is 1 year and E_{fos} is the scale of the present power generation from fossil fuels, and E_{sell} cannot exceed this value. The production amounts of raw sugar, molasses and bagasse are also evaluated to analyze the effect of the cultivar change on mass balance in the sugar mill.

Table 3-16 Case settings on technology options

	Cultivar	Power turbine			Selling electricity in a period without sugar production
		Type	Inlet	Outlet	
Case A	Standard cultivar	BPST[1)]	344ºC, 1.85 MPa	140ºC, 0.08 MPa	×
Case B1	KY01-2044	CEST[2)]	480ºC, 6.5 MPa	140ºC, 0.08 MPa	×
Case B2	KY01-2044	CEST[2)]	480ºC, 6.5 MPa	140ºC, 0.08 MPa	○

1) BPST: Back Pressure Steam Turbine, 2) CEST: Condensing Extraction Steam Turbine

Table 3-17 Current power supply configuration (Estimated from OEPC (2014a), OEPC (2014b), OEPC (2014c) and OEPC (2014d))

	Thermal [MW]	Photovoltaic [MW]	Wind turbine [MW]
Okinawa	1,930.0	0.0	0.0
Ishigaki	88.0	8.9	0.0
Miyako	80.0	10.7	4.8
Kume	18.5	1.5	0.0
Minami-Daito	3.6	0.0	0.5
Kita-Daito	1.5	0.1	0.0

Table 3-18 shows the settings of the milling capacity [t d^{-1}] and actual one [t d^{-1}] for each sugar mill in this study. The grid of Izena Island is interconnected with that of Okinawa Main Island via submarine cable (CAO, 2010). The data of milling capacities were from a report in 2015/2016 (Japan Centrifugal Sugar Industry Association, 2016), and actual ones are 90% of the milling capacities. Some parameters in the mills such as the ratio of maceration water addition to fiber, bagasse water content, electricity consumption, the rated power output of BPST were based on interviews with on-site engineers. The others referred the data collected in Chapter 3.2. Farmland areas [ha] for cropping types around each sugar mill, and the standard cultivar and its yield per farmland area there are shown in Tables 3−18 and 3−19, respectively. (The detailed explanation of cropping types are described in

Chapter 3.2.2. They have influences on the sugarcane yield and its composition). The farmland areas and the yields of the standard cultivars were estimated as the values of the average from 2009 to 2015 (Okinawa Prefecture, 2017).

Table 3-18 Properties of sugar mills and performance of sugarcane in Okinawa, Japan

Island (Sector of Power system)	Symbol	Company name	Milling capacity [t/d]	Actual milling capacity [t/d]	Area [ha]	Cropping type		
						Summer-planted [ha]	Spring-planted [ha]	Ratoon [ha]
Okinawa	YGF	Yugafu Seito K.K.	2,100	1,890	3,342	393	547	2,401
		(Northern and middle parts)			1,673	230	309	1,134
		(Southern part)			1,669	163	238	1,267
Izena (Okinawa)	IZN	JA Okinawa, Izena branch	300	270	348	59	72	217
Kume	KMJ	Kumejima Sugar Mfg. Co., Ltd.	800	720	968	194	157	617
Minami-Daito	MDT	Daito Sugar Mfg. Co. Ltd.	850	765	1,214	81	218	915
Kita-Daito	KDT	Kita-Daito Sugar Mfg. Co., Ltd.	360	324	392	24	84	284
Miyako	MYO	Okinawa Sugar Mfg. Co., Ltd.	1,900	1,710	1,814	1,179	138	496
	MYG	Miyako Seito Co., Ltd., Gusukube Factory	1,800	1,620	1,622	1,049	146	427
	MYI	Miyako Seito Co., Ltd., Irabu Factory	490	441	819	712	32	75
Ishigaki	ISH	Ishigakijima Sugar Mfg. Co., Ltd.	1,000	900	1,283	766	165	352

Table 3-19 Performance of standard sugarcane cultivar in Okinawa, Japan

Island (Sector of Power system)	Symbol	Standard cultivar	Unit yield of standard cultivar			Reference data of crops
			Summer-planted [ha]	Spring-planted [ha]	Ratoon [ha]	
Okinawa	YGF					
		NiF8	54.3	34.6	38.0	G1
		Ni9	75.1	49.2	55.7	G2
Izena (Okinawa)	IZN	NiF8	58.7	37.0	41.9	G1
Kume	KMJ	NiF8	65.7	43.9	45.7	G1
Minami-Daito	MDT	NiF8	65.2	41.8	43.7	G1
Kita-Daito	KDT	NiF8	55.1	33.7	34.7	G1
Miyako	MYO	Ni15	79.9	58.5	57.1	G3
	MYG	Ni15	74.8	47.6	49.7	G3
	MYI	Ni15	69.9	44.3	43.8	G3
Ishigaki	ISH	Ni15	70.4	50.0	46.4	G3

The yield and composition of chosen cultivar can be obtained in reference to the data sets that are divided into three groups shown in Tables 3−20a and b. These groups were classified based on the locations of the farmlands. Nago, Itoman and Miyako are one of the cities of northern and middle parts of Okinawa Main Island, southern part of Okinawa Main Island and Miyako Island, respectively, and the cultivation data there are obtained as shown in the table. With regards to the regions lacking in the data, a group of the region whose soil type is the same or whose location is the closest to was chosen. The table shows the data sets of the yield performances and compositions of both the standard cultivar and KY01-2044 for each reference group. As the yield performance, the ratio of the yield of the chosen cultivar to that of KY01-2044 was chosen. In other words, the yield can be calculated by multiplying the yield ratio shown in Tables 3−20a and b with the yield of the standard cultivar in Table 3-19. The composition of each cultivar was based on the actual data of cultivation (MAFF, Japan, 2014), which had recorded for cultivars, cropping types and regions. Because the data related to summer-planted are lacking, the composition of the summer-planted crops was estimated as the same as that of the spring-planted ones. For simplicity's sake, mass flow from cane tops and leaves of sugarcane are excluded in this study.

Table 3-20a Characteristics of sugarcane cultivars for Japanese region (Spring-planted case)

Group name	Region	Cultivar	Spring-planted				
			Yield ratio [-]	Sucrose [%]	Fiber [%]	Brix [%]	Purity [%]
G1	Nago	NiF8	1.00	15.2	10.8	16.9	90.2
		KY01-2044	1.60	13.2	13.1	15.3	86.3
G2	Itoman	Ni9	1.00	14.5	11.4	16.3	88.9
		KY01-2044	1.08	13.9	11.7	16.1	86.6
G3	Miyako	Ni15	1.00	11.8	10.0	13.5	87.3
		KY01-2044	1.35	9.6	12.3	12.2	79.0

Table 3-20b Characteristics of sugarcane cultivars for Japanese region (Ratoon case)

Group name	Region	Cultivar	Ratoon				
			Yield ratio [-]	Sucrose [%]	Fiber [%]	Brix [%]	Purity [%]
G1	Nago	NiF8	1.00	16.1	10.6	18.9	85.2
		KY01-2044	1.30	15.0	12.9	18.3	81.8
G2	Itoman	Ni9	1.00	14.1	11.9	15.9	88.7
		KY01-2044	1.52	13.6	12.9	15.9	85.8
G3	Miyako	Ni15	1.00	11.8	10.4	13.8	85.7
		KY01-2044	1.75	8.6	14.1	10.8	80.0

Simulation results

Figure 3-26 shows the simulation results of annual production amounts of raw sugar, molasses and bagasse and operating days for each sugar mill. Case B1 and Case B2 are shown as Case B together in one case because the results of them are the same. For all mills, the annual production amounts of raw sugar, molasses and bagasse in Case B are larger than those in Case A in spite of the difference in the scale of milling capacity. These are because KY01-2044 grows larger than the standard cultivar (see Tables 3−20a and b) and, hence, the processing amount of KY01-2044 is larger. These tendencies are consistent with a previous report (Ohara et al., 2009). The increases in raw sugar are not as remarkable as those in molasses and bagasse because the sucrose content in KY01-2044 is lower than that in the standard cultivar (see Tables 3−20a and b). Comparing the ratio of raw sugar production in Case A to the increment in Case B among the islands, 29% in YGF is the highest and 7% in MYI is the lowest. It takes the larger number of operating days in Case B than in Case A for all islands. The length of the operating is in proportion to the yields of crops if the milling capacity is the same.

Comparing the number of extended days in Case B from Case A among the islands, 46 days in MYI is the largest, whereas 16 days in KDT is the lowest.

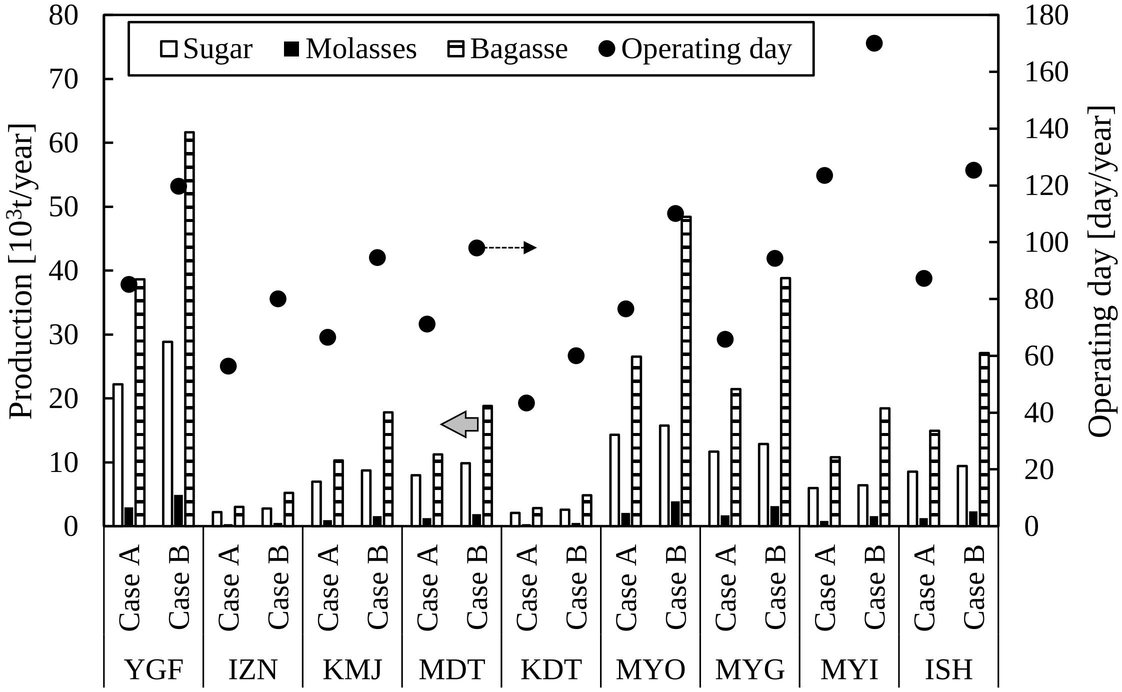


Figure 3-26 Simulation results of sugar, molasses and bagasse production and operating days for sugar mills in Okinawa Prefecture. The vertical axis on the left side is used for bar graphs of production amount of sugar, molasses and bagasse, whereas that on the right side is used for plots of operating day. Case B1 and Case B2 are shown as Case B together in one case because the results of them are the same.

Figure 3-27 shows the breakdown of energy consumption in the sugar mills in a period of sugar production. Energy obtained from bagasse combustion in this season is converted into either of the followings: heat for sugar production, surplus heat in the form of LPS, electricity for sugar production and for selling. The heat for sugar production is dominant regardless of the cases, whereas surplus LPS is generated in Case B1 for all mills. The provision of LPS in Case B1 is in proportion to bagasse produced, whereas the demand of LPS is in proportion to raw sugar produced. Therefore, the generation amount of LPS is smaller in IZN and KDT, where the ratio of bagasse to raw sugar production is relatively small, than that in the other mills. The energy converted into electricity for selling in Case A is less than that in Cases B1 and B2 for all mills. Case B1 can convert larger amount of energy from bagasse into electricity in higher efficiency compared with Case A1, but generated surplus LPS may be wasted unless there are its consumers in the neighboring area. Case B2 does not generate surplus LPS because bagasse is fueled at an appropriate rate in the sugar production period, but the scale of selling electricity is smaller than that in Case B1.

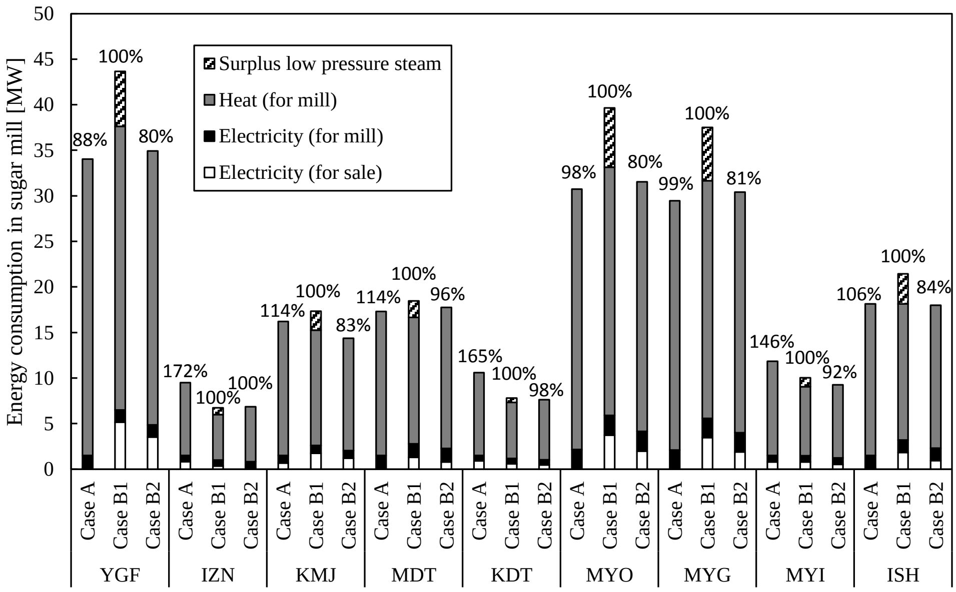
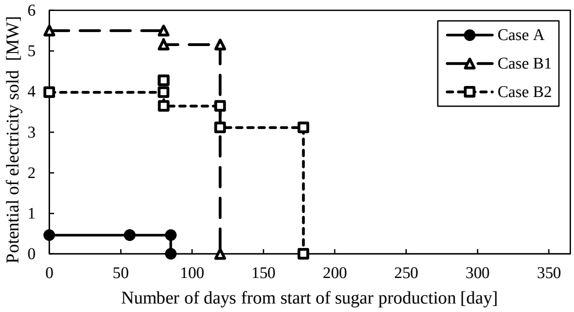
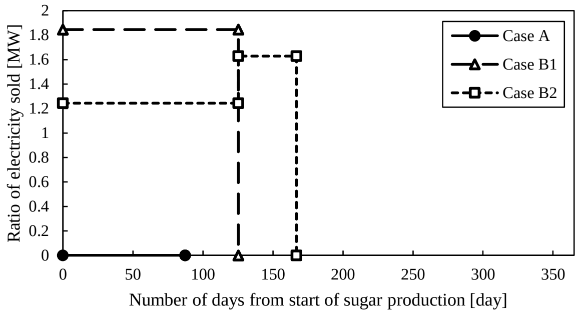


Figure 3-27 Breakdown of energy consumption in sugar mills in a period of sugar production. The ratio of energy consumption to the energy from all bagasse is presented on the top of bar graphs. Electricity consumption is shown as the secondary-energy-based value.

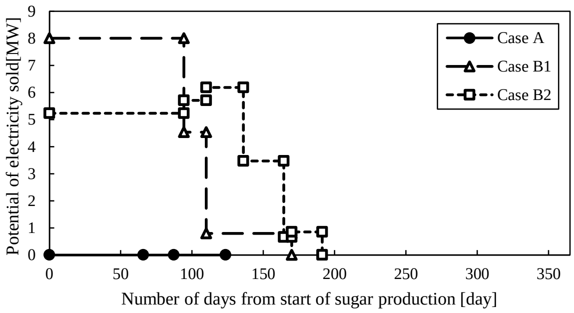
Figure 3-28 shows the scale of electricity sold from the start of sugar production for islands. For example, in Kume Island (Figure 3-28d), 0.12 MW is continuously sold as surplus electricity until the 66th day in Case A. Because the scale of generating electricity reaches the current rated power output during this term, surplus bagasse is generated, but it is not used in the off-season in this case. Therefore, electricity is not sold after the 66th day. In Case B1, 1.76 MW is sold until the 95th day with the consumption of all bagasse generated. In Case B2, 1.24 MW is sold as surplus electricity until the 95th day with storing surplus bagasse, which is used as fuel for selling electricity from the 95th day to the 127th day in 1.30 MW. As Okinawa Main Main Island (Figure 3-28a) and Miyako Island (Figure 3-28c) have two and three sugar mills, respectively, the summation of the scale of electricity sold from those mills are shown in the figures. The area bounded by a polygonal line, a horizontal axis and a vertical axis represents the annual electrical energy for selling. For all cases, Miyako Island can produce the largest amount of electrical energy for selling of the six islands. From this figure and Table 3-17, the scale of the electricity sold from bagasse do not exceed that from fossil fuels. Comparing the duration of selling electricity in Case B2 among the six islands, Miyako Island shows the longest. In this case, it is possible for Okinawa Main Island, Kume Island, Minami-Daito Island, Kita-Daito-Island and Ishigaki Island to sell electricity until the 178th, 127th, 105th, 62th and 167th day, respectively. Comparing among cases, both the scale of electricity sold and the duration of the selling in Cases B1 and B2 are larger than those in Case A. There is a trade-off relation between the scale and the duration regarding Cases B1 and B2.



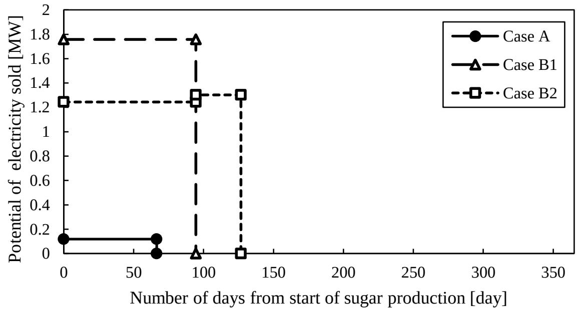
a. Okinawa Main Island (YGF, IZN)



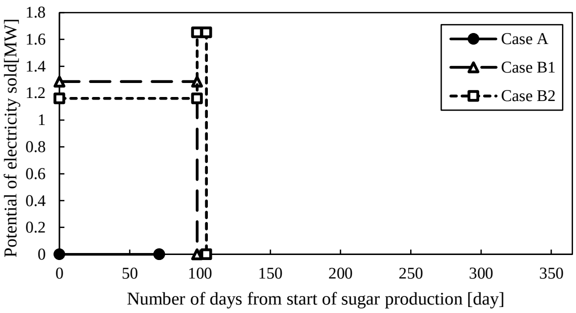
b. Ishigaki Island (ISH)



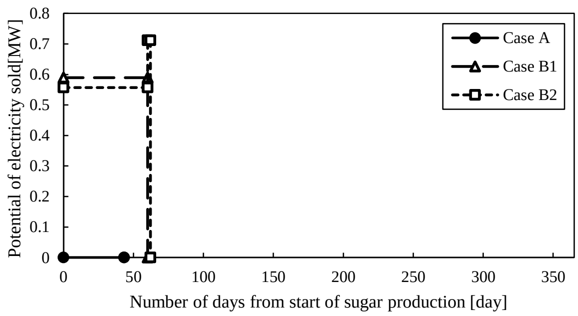
c. Miyako Island (MYO, MYG, MYI)



d. Kume Island (KMJ)



e. Minami-Daito Island (MDT)



f. Kita-Daito Island (KDT)

Figure 3-28 Simulation results of potential of electricity sold in islands in Okinawa prefecture.

Figure 3-29 shows *SR* for each island. *SR* in Case A is almost 0% for all islands, whereas higher *SR* is presented in Cases B1 and B2. Minami-Daito Island shows the highest SR among six islands, representing 9.48% in Case B1 and 9.39% in Case B2, followed by Kita-Daito Island, Miyako Island, Kume Island and Ishigaki Island. The lower the electricity demand in the island against the scale of the electricity sold from sugar mills, the larger *SR* becomes. *SR* in Case B1 is slightly higher than that in Case B2 for all islands. This is because the power conversion efficiency only in the period of sugar production in Case B1 is higher than that in the period including the off-season in Case B2.

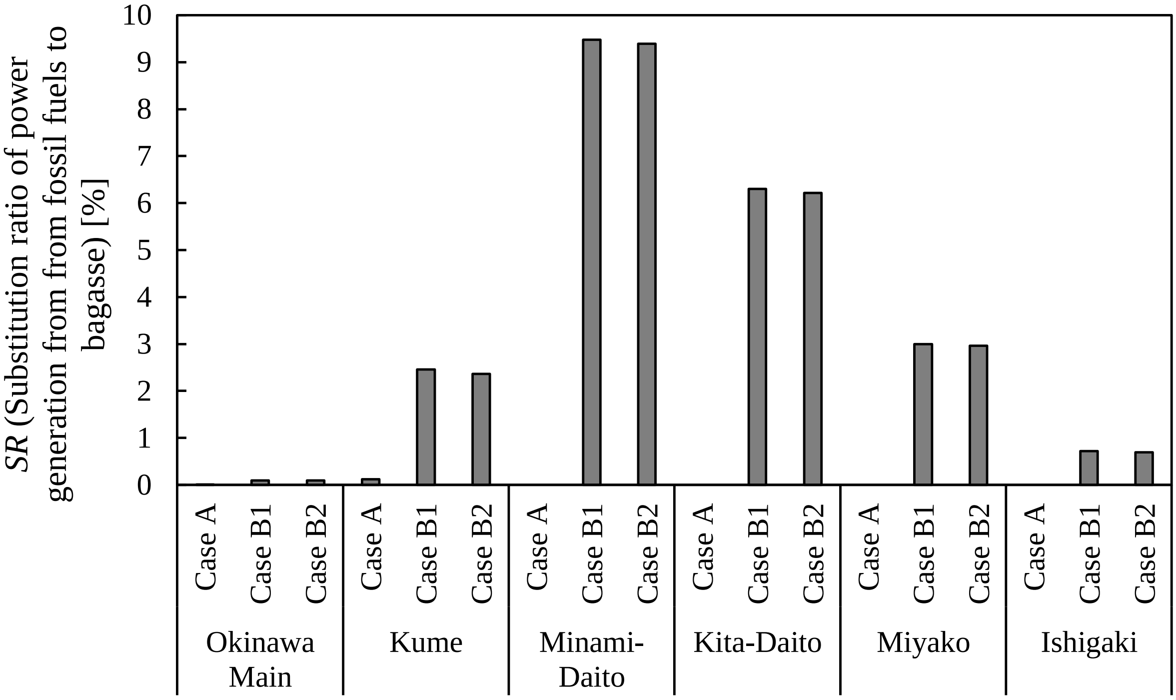


Figure 3-29 Bagasse production and consumption for Okinawa Islands. SR is substitution ratio of power generation from fossil fuels to bagasse.

3.4.4. Discussion

Alternatives considering technology options and managements

As Figures 3−26 and 3−28 indicate, considering the technology options on sugarcane cultivar and the power plants in sugar mills in simulation raise awareness of new alternatives such as Cases B1 and B2 that can enhance the ability of the mills to sell electricity with the increases in annual raw sugar and molasses productions. While there is not much difference in *SR* between the two cases, they differs in the seasonal dependence of the scale of electricity sold as confirmed from Figure 3-29. It is necessary to consider the seasonal variation of the electricity demand in the region for their evaluation. For example, Case B2 is better than Case B1 in the region where the scale of the electricity demand in the period of sugar production (in general, this period is from December to April for sugar mills in Japan) is lower than that of the electricity sold in Case B1. As another point for the comparison, Case B2 in the off-season enable a more flexible operation toward fluctuation in the electricity demand than Case B1 because the electrical output in that season can be controlled to some extent by adjusting the rate of fueling bagasse. On the other hand, controlling the scale of the electricity sold in the sugar production period is not easy because it depends on the heat and electricity demand of sugar production.

Since the surplus heat is generated in the period of sugar production in Case B1 as shown in Figure 3-27, its use for other purposes may reduce the loss of bagasse-derived energy. Ethanol production from molasses produced in the sugar mill is one of the solutions to consume the surplus heat. Providing the ethanol plant with molasses and heat can save the cost for fossil fuels and their transportation. Some technology implementations such as chemical heat storage and transfer (e.g. Fujii et al., 2015) may enable ethanol production even in the off-season or at some distance from the mill.

To improve the ability of sugar mills to sell electricity, further expansion of the scale of selling electricity and the number of days for the selling is desired. Other alternatives can be discussed as follows based on the above results of Cases A, B1 and B2. One of the alternatives is collecting other regional biomass resources and combusting bagasse with them together (Kikuchi et al., 2016b). Replacing the current boiler with the one that can apply to the mixed combustion may expand the scale or the number of the days because of the increase in fuels. Another alternative is saving energy consumption in the sugar production. The saved energy can be used for producing electricity. As ways for saving the energy, utilization of stem extracted from multiple-effect evaporators as heat source for other process (Rein, 2007), saving water addition in the crystallization pans and the centrifugal separators (Rein, 2007), replacement of roll mills with ones powered by electricity, and detailed heat integration of the whole mill (Ensinas et al., 2007) can be considered.

Effect of implementing bagasse power plants in remote islands

Implementation of bagasse power plants in the remote island contributes to the diversification of the power resources there through partly replacing the power generation from fossil fuels. To date, the energy security of microgrid in the remote islands greatly depending on fossil-derived power has been vulnerable. The electricity price has been subject to effects of social changes such as fluctuation in the price of fossil fuels and legal revision. For example, the liberalization of electricity retail sales that was launched in 2016 and the separation of electrical power production from power distribution and transmission that will be launched in 2020 in Japan may cause the leap in electricity price in the region where importing fossil fuels is costly like remote islands in Okinawa Prefecture. On the other hand, bagasse is already an available resource in these regions as long as cane sugar industry lasts. In addition, power plant using bagasse is not interfered with by everyday weather condition unlike power plant from photovoltaic or wind turbine power plant. On the contrary, it may supplement the gap between the electricity supply and demand.

The combined raw sugar, electricity and ethanol production from sugarcane discussed in this section are in the scope of birorefinery concept. The process systems design based on this concept may contribute to sustainability in cane sugar industries through the reduction of GHG emissions, the improvement in economy (e.g. Silalertruksa et al., 2015) and employment creations (e.g. Moncada et al., 2013; Gheewala et al., 2011). The cane sugar industry is the main industry of the remote islands in

Okinawa Prefecture. Although it has supported the regional economy, the population of farmers has been decreasing recently because of the aging and outflow of population. Using regional biomass resources including bagasse for selling electricity or providing heat for a new business discussed above may reduce the outflow of money with the saving of fossil fuels and create employment. As a consequence, the activation of economic circulation and the improvement in socio-economy in those regions can be expected (Kikuchi and Oshita, 2015)

Future works for implementing bagasse power plants

One of the obstacles to conduct the above alternatives is difficulty in having farmers plan the cultivar change. The price of sugarcane is determined by its sucrose content in Japan (MAFF, Japan, 2015b). As discussed in Chapter 3.2.5, it is difficult to motivate famers to choose low-sucrose cultivars such as KY01-2044 under the current policy. In addition, if the number of operating days increases because of choosing KY01-2044, some unpleasant results for farmers may be caused. If the cropping season delays, farmers may not spend time enough to prepare the soil for the next crop. If the harvesting schedule is moved forward, farmers have to harvest immature crops, resulting in the drop in their income. To motivate farmers to choose KY01-2044, all of the components including the fiber, which can contribute to electricity generation, should determine the value of sugarcane.

The effects of the cultivar change to KY01-2044 on soil fertility are also concerned. Although it brings larger amount of nutrients from the soil compared to NiF8, returning by-products as fertilizers to the farmland would be one of the solutions as discussed in Chapter 3.2.5.

Possible Evolution into Ancillary Service

As the number of power plants using intermittent energy source such as photovoltaic and wind power increases, stabilizing the quality of the grid become one of the challenges especially in the microgrid of remote islands where reciprocating engines are mainly used for power generation (Ogawa, 2017). The capacities of these power plants reach the upper limit in some remote islands (KyushuEPCO, 2014). Compared to turbines, reciprocating engines has lower inertia to help overcome the initial frequency/speed change, mainly due to its low speed (Tian and Crous, 2013). This is why many remote islands are at a disadvantage in achieving both renewable and stable power generation.

Recently, the creation of a market for ancillary services has begun to be planned in Japan for providing electricity in a stable quality (Asano, 2014). According to Federal Energy Regulatory Commission, ancillary services are defined as “those necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system (Edison Electric Institute, 1995).” Bagasse power plants may play a role in facilities to offer ancillary services by interconnecting with the grid since they use a turbine for power generation. The detailed discussion on the possibilities for ancillary services will be expected by further simulation-based analysis considering the frequency fluctuation of the grid based on the results of this simulation.

3.5. Summary

A model of combined raw sugar and bioethanol production integrating agricultural and industrial processes, named SugaNol, was constructed in Chapter 3.2. This model can describe the material flows from sugarcane cultivation to raw sugar and bioethanol production. Two case studies (Case studies A and B) were undertaken to demonstrate the potential of the model. In Case study A, the relationship among the quality of syrup, the utilization network of molasses and seed crystals, and the process performance such as the sugar yield, the consumption of the energy, and the crystallization pan load were analyzed. It was revealed that the effect of fluctuation in syrup quality that comes from agriculture can be alleviated by an adequate modification in industrial operations with tight scheduling. Case study B demonstrated that performance aspects i.e., productivity, economy and reduction in environmental impacts can reach to a degree that earlier progress in elemental technologies has never achieved by simultaneous implementation of both agricultural and industrial technology options.

In Chapter 3.3, a process model was extended from the SugaNol to examine the system-wide effects of introducing SF into sugar mills considering the type of sugarcane cultivars. Using the model, a case study was performed to compare the productivity and the operability of the proposed system where the high yielding cultivar is chosen and SF is introduced with those of the current system. The results of the case study demonstrated that the proposed system could enhance both raw sugar and ethanol yield without additional fuel oil A and simplify the operations in the crystallization process with reducing the working time of the crystallization pans. Although the economic feasibility remains an issue, SF has a potential of cutting the investment on existing crystallization pans or increasing raw sugar yield by sparing more time on each crystallization batch. To improve the economic feasibility or enhance the productivity of mills in the future, cultivars that show excellent characteristics on unit yield and resistance rather than compositions should be looked for through plant breeding because SF can mitigate the negative impacts of low sucrose content and purity on the productivity and the operability in sugar mills. These discussions indicate that a modeling approach assists the coordinated transformation of farming and sugar milling by identifying desirable and feasible alternatives in design stages.

In Chapter 3.4, an implementation analysis of bagasse power plants interconnected with the main grid of the remote island was conducted considering the technology options on sugarcane cultivar and the power plants in sugar mills. SugaNol was further extended to estimate the mass and energy balance of a cane sugar mill for the type of the cultivar and power plant. For all target islands, the period and the scale of selling electricity can be expanded with the increase in raw sugar production if sugarcane cultivar and the power plants in sugar mills are changed simultaneously. Effective utilization of surplus heat, mixed combustion of bagasse with other regional biomass and savings in the energy demand of the cane sugar mills may further enhance the positive effects of introducing bagasse power generation.

Through this chapter, the effectiveness of the integrated modeling approach were confirmed. The outcome of case studies on sugarcane-derived production demonstrated that systems performance aspects can reach to a degree that earlier progress in elemental technologies has never achieved due to a greater space of solution that is now possible to explore exhaustively. However, this static simulation alone cannot sufficiently discuss the temporal aspect, e.g. the time required for the transition. It can be emphasized that how to use this model for future planning is crucial to the practicability. In the next chapter, the way of using this model in scenario planning is examined.

Chapter 4. Scenario Planning Considering Time Scales and Future Uncertainties: A Case Study on a Cane Sugar Mill

4.1. Introduction

Chapter 3 demonstrates that an alternative candidate that exists outside the present vision can be generated by considering the agricultural and industrial options as variables simultaneously. However, the transition to such candidates sometimes needs complex procedures, which may prevent the players from making clear decisions for the following two reasons.

First, the easiness of a transition strongly depends on the orders of measures. An alternative candidate generated from the method proposed in Chapter 3 would be a novel one involving multiple decision makers in both agriculture and industry. As one's decision potentially affects others' decision, the barrier height for taking a decision may change. All potential decision makers should build consensus of their future actions in advance and make a decision with an awareness of what it will bring to others.

Second, the transition takes years of time in many cases, especially in agriculture, while the situation could change from the present. For example, since plant growth generally needs several months and years, the outcome of the modification in cultivar choice or farm operations will be obtained with a time delay. In addition, there are innumerable farmers in agriculture and it is not realistic to change all their decisions simultaneously. Instead, a gradual change in agriculture would be expected. During such transition, some regulations may change, the lifetime of equipment in a factory may approach the end, or technological level may progress. Future uncertainties should be taken into account in the time scale of years.

For these reasons, an activity for reaching the alternative candidate considering the time scale and future uncertainties are strongly needed to make the generated alternatives practicable. Scenario planning is a technique to articulate the mental models about the future to make better decisions (Martelli, 2001; Amer et al., 2013) and could facilitate to reach the goal. The scenario planning for the candidate, however, would require a new insight for players. Figure 4-1 schematically shows the present and extended vision and scenarios. They have to share information about a constraint for other players to make a required decision and discuss how to remove it considering the options they have. Because this is an untrodden approach, whether it functions as a mechanism for generating more practicable scenario should be verified. To this end, a case study of scenario planning is conducted in this chapter.

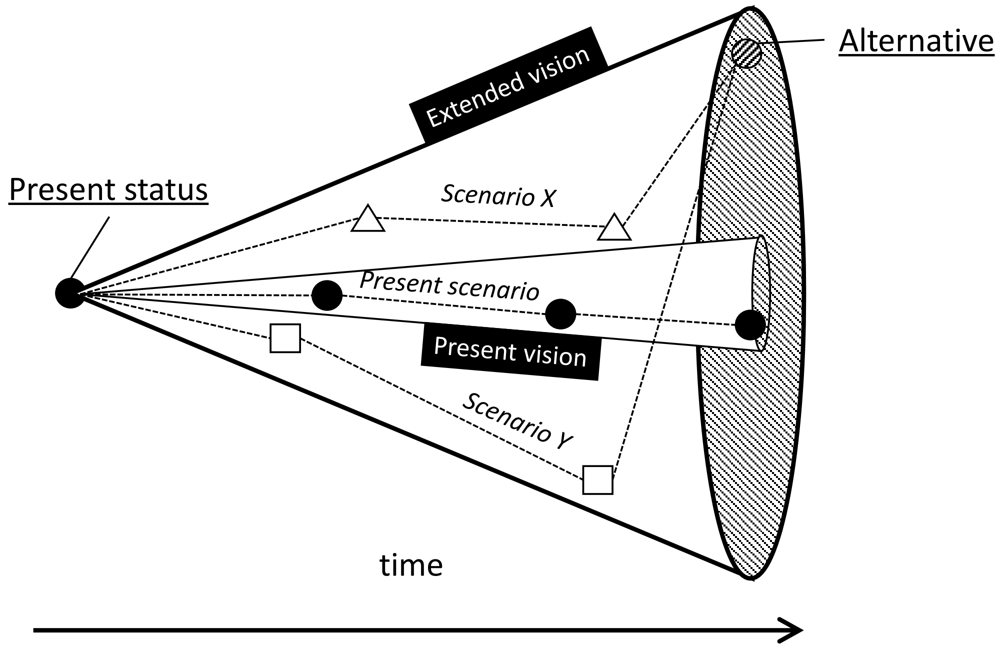


Figure 4-1 Present and extended vision and scenarios.

4.2. Materials and Methods

A scenario planning meeting is held in Shinko Sugar Mill Company, which is one of the Japanese cane sugar mill companies and located in Tanegashima Island. The participants are engineers and managers in in the company. Some engineers work as part-time sugarcane farmers at the same time. In other words, people who are well versed in either or both sugarcane farming and milling take part in this meeting.

Before the meeting, the present condition of the targeted sugarcane industry and the social event that may happen or be planned in the future are investigated. The information of durable year of the existing apparatuses and their planned renewal year is collected via interviews with the engineer. Based on the investigation and using SugaNol (see Chapter 3.2-3.4), scenario candidates are prepared. These scenario candidates are used for discussion in the meeting. Through this meeting, it is observed whether the constraint for performing the scenarios and countermeasures for removing the constraint could be generated on the participants' own.

4.3. Scenarios Generation for Transition to Intensified Agriculture and Industry

There is no doubt that the existing sugarcane industry is desired to sustain its business in Tanegashima Island. It does not only create farming and sugar milling employments, but also strongly supports regional economy in the island. According to a statistics issued by Kagoshima Prefecture (2017), the sugarcane production accounts for 18.7% of gross agricultural production in the island. Surplus bagasse generated in the sugar mill is indispensable for livestock industry to get bedding for livestock. From the viewpoint of the nation, it is important to maintain a certain level of the domestic sugar production in terms of the national food security.

Despite the above desire, there is a threat of wrecking the sugarcane industry in the future. Figure 4-2 shows the estimation of the future population in Tanegashima Island. The population is expected to decrease constantly. According to the on-site engineers, 50% of current feedstock in weight have to be kept to sustain the business.

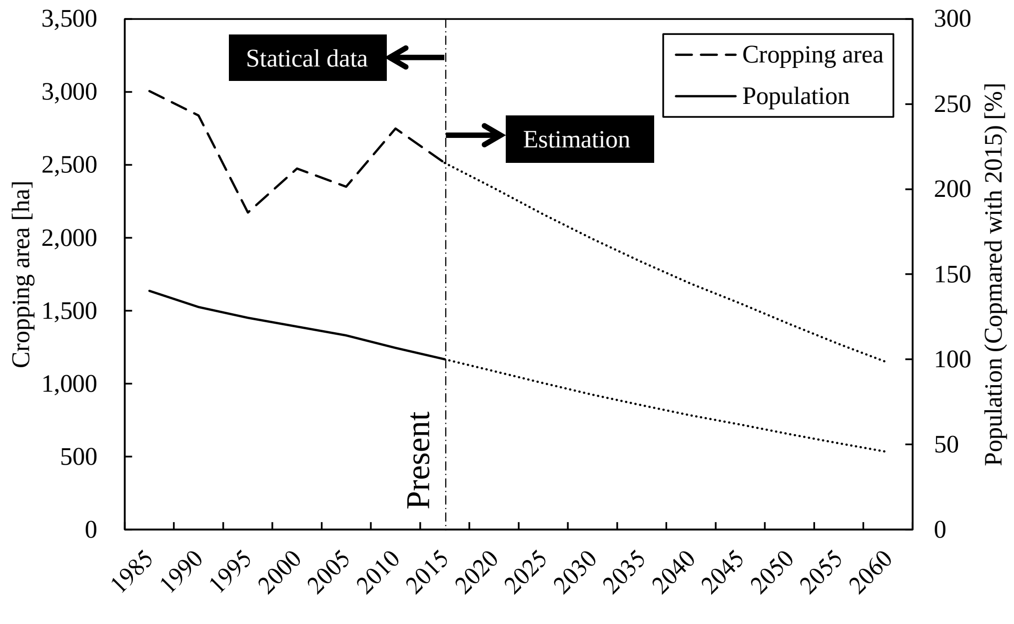


Figure 4-2 Estimation of the future population and cropping area in Tanegashima Island. Population until 2010 is based on statical data, that until 2040 is based on estimated record issued by IPSS (2013) and that after 2040 is based on quadratic approximation from the data from 2010 to 2040. Cropping area until 2015 is based on statical data and that after 2015 is in proposion to the ratio of population in the year to that in 2015.

The future cropping area can be expected to decrease in proportion to the population decline considering the recent trend. Figure 4-3 shows the historical transition of cropping area, the ratio of farmers who introduce a harvester (one of the agricultural machinery, and see Chapter 3.2.3) into farming and population in Tanegashima Island (Nakatane Town, 2015; Nishiniomote City 2017). The population has been constantly decreasing. The current population is 70% of that in 1982. Despite the population decline, the cropping area has maintained its range between 2,000 and 3,000 ha since 1990. This might be because of the increase in the ratio of farmers who introduce a harvester into farming. While population has decreased, farmers might have struggled to maintain the cropping area by reducing their working loads with the harvester. However, it would be difficult to maintain the area continuously in the future because the introduction ratio is approaching to the upper limit.

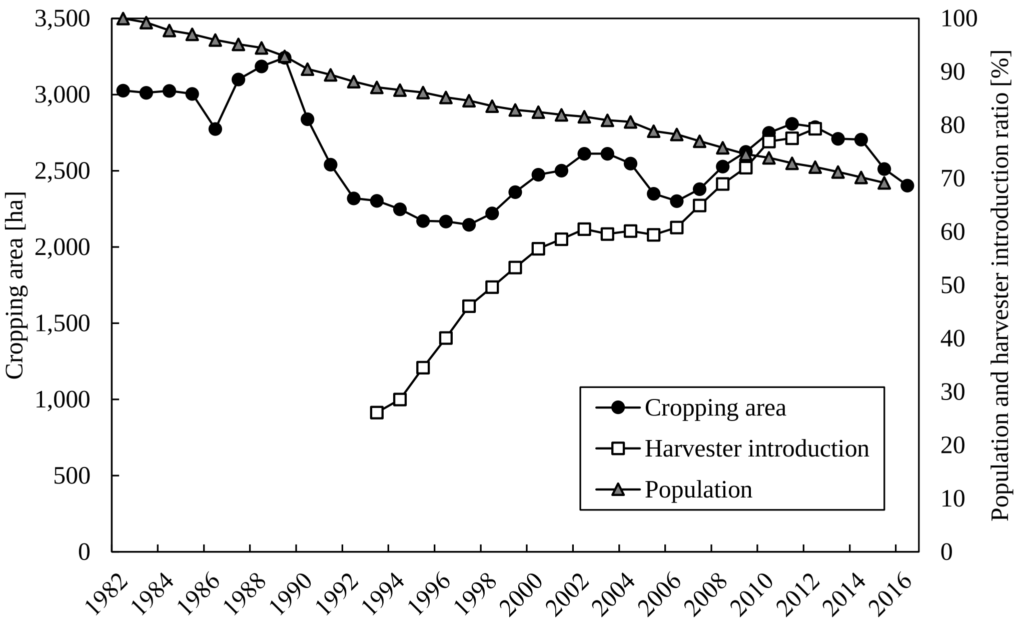


Figure 4-3 Historical transition of cropping area, the ratio of farmers who introduce a harvester into farming and population in Tanegashima Island. The triangular plots represent the ratio of the population to that in 1982.

If the future cropping area would decrease in proportion to the population decline, the area in 2056 will drop below 50% of that in 2015 as also indicated in Figure 4-2. 40-year vision should be developed to avoid the undesirable future.

As a social change that will happen in 40 years, the rise in the electricity price is expected. In Japan, liberalization of retail electricity sales was launched in April, 2016 and separation of electrical power production from power distribution and transmission is planned in April, 2020, when electricity price is completely deregulated. The electricity price in Tanegashima Island has been the same as that in other area in Kyushu under the current regulation. Because the electrical power production in remote island is generally costly (see Chapter 3.4.1), the local electricity price may rise after the deregulation. Currently, the mill do not have motivation to sell electricity to the grid. The rise in the electricity price can be a driving force for the mill to start selling electricity.

With regards to other social changes, the heat-transporting pipe from the mill to the neighbor village is planned to be constructed. Once it is completed, waste heat from the mill could be transported to the consumer in the village. In addition, completion of the technology for heat storage and transport developed by Fujii et al. (2016) could supply the waste heat in the off-season. Regional woody biomass may be also available as fuels for the mill if the forestry is appropriately managed and the boiler in the mill is replaced with a mixed-combustion-type one (Kikuchi et al., 2016b).

Under such social changes, farmers and the sugar mill can take measures as follows: Farmers can choose the existing high-yielding cultivar instead of the current one, while the mill can increase bagasse by energy saving with the reexamination of the process or drying bagasse, replace apparatus with new one after the end of its payback time, construct an ethanol plant and start the business of selling ethanol, electricity, and heat.

The order of the measures should be determined carefully considering the expected outcome and driving force of the action. Table 4-1 organizes the action, its expected outcome and driving force for each player. For example, it is not until regional heat-transporting pipe is prepared that the mill can sell waste heat. Saving energy consumption in the cane sugar mill and the preparation of surplus bagasse usage should be conducted simultaneously to minimize the deficiency and excess of the bagasse. Surplus bagasse should be increased before starting ethanol production or selling heat considering the energy balance in the mill.

Paying attention to the relationship in Table 4-1, scenario candidates are generated. The scenarios are divided into two types, that are scenarios A and B, depending on the timing of electricity price deregulation because it could change the type of the boiler and turbine that should be chosen for the replacement.

Figure 4-4 shows Scenario A where the electricity price deregulation launch comes earlier than boiler and turbine replacement dues. This is an optimistic case because the mill can replace with confidence assuring the electricity will be sold at higher price compared with the present. After the rise in electricity price, the mill can choose the better choice from electricity-used or heat-used business. If electricity-used business is promoted, the current BPST should be replaced with CEST. Electrification of the mill turbine may save the energy loss and increase the electricity selling potential, although the trade-off between the reduction of heat demand and the increase in electricity demand should be examined in detail. If heat is promoted to use, BPST is updated to the same type and waste heat is provided during sugar production and in off-season. There are two kinds of heat usage: ethanol production from molasses near the mill and the regional consumption via the regional heat-transportation pipe if already available. The transported heat can be used as the energy source of district heating or cooling. The temporal controllability of heat provision becomes more flexible if the technology of heat storage and transport is completed.

Table 4-1 Action, expected outcome and driving force for each player

Key player	Action	Expected outcome	Driving force
Mill company	Enegy saving	Increase in surplus bagasse (biomass)	Heat consumer
Mill company	Ethanol production	Increase in income of mill company	Increase in biomass
Mill company	Heat selling	Increase in income of mill company	Rise in fuel prices
			Infrastructure or technology for selling
Mill company	Electricity selling	Increase in income of mill company	Rise in electricity prices
Mill company	Replacement of BPST with CEST	Increase in electricity generation	Expect of investment return
Farmer	Diffusion of high-yielding sugarcane	Increase in surplus bagasse (biomass)	Time
Power company	Raising electricity price	Rise in electricity prices	Electricity price deregulation
Forestry	Increase in available woody biomass	Increase in biomass	Time
Technology developer	Development of heat storage system	Increase in income of mill company	Time
Town	Preparation of regional heat-transporting pipe	Incentive for selling heat	Time
Government	Electricity price deregulation		
Society	Rise in fuel prices		

Scenario B is further divided into two, Scenarios B1 and B2, depending on whether ethanol production is implemented or not. Figure 4-5 shows Scenario B1 where electricity price deregulation launch comes later than boiler and turbine replacement dues and ethanol production is not considered as an option. In contrast to Scenario A, the replacement of the existing BPST with CEST is less motivated in this scenario because it is not certain whether the excess electricity can be sold at higher price compared with the present or not. Nevertheless, the mill engineers have to start from what they can do just now in order to avoid the unpleasant future. It is already possible for the mill to take measures for increase in bagasse by saving the energy consumption or installing the equipment for drying bagasse. After the regional heat-transporting pipe is prepared, the mill can smoothly start selling heat. This waste heat can be used for ethanol production as shown in Scenario B2 (Figure 4-6). In this case, the ethanol plant will remain a heat consumer after the renewal of BPST.

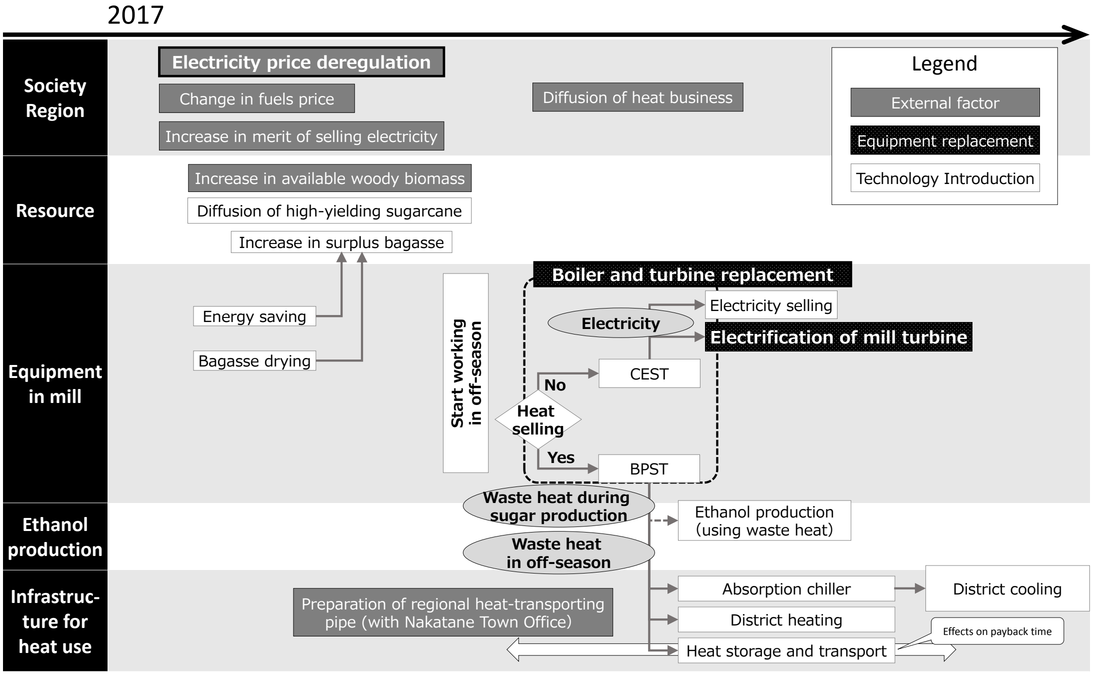


Figure 4-4 Scenario A: The case where electricity price deregulation launch comes earlier than boiler and turbine replacement dues. (CEST is a condensing-extraction steam turbine. BPST is a back-pressure steam turbine. The figure is translated from the actual poster written in Japanese. The same applies Figures 4−5 and 4−6).

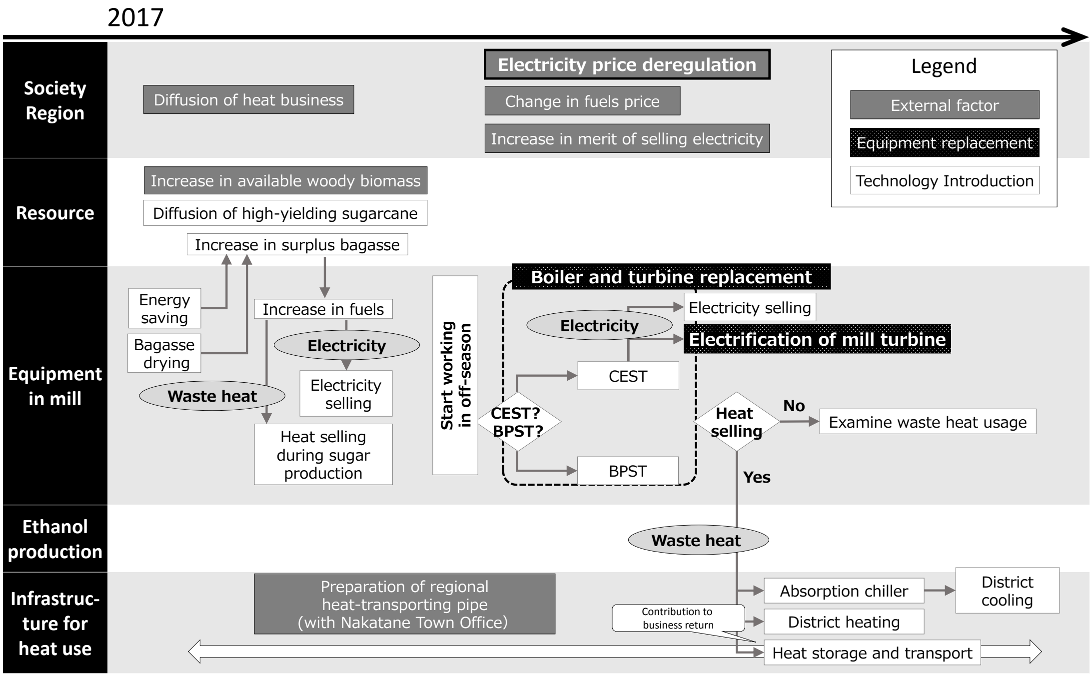


Figure 4-5 Scenario B1: The case where electricity price deregulation launch comes later than boiler and turbine replacement dues and ethanol production is not considered as an option.

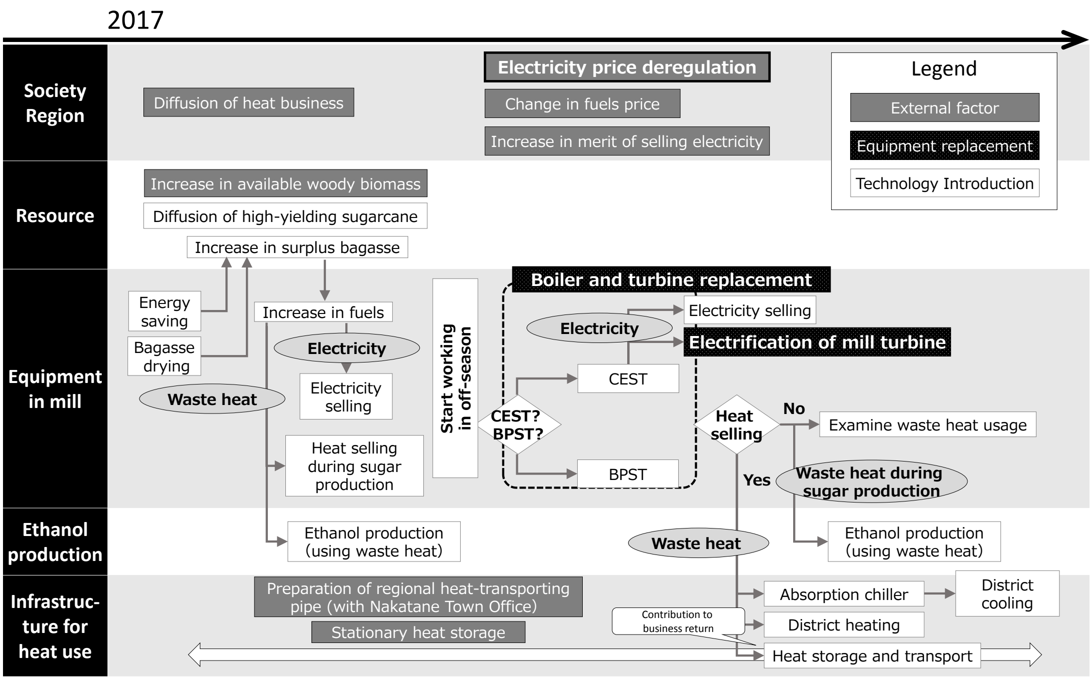


Figure 4-6 Scenario B2: The case where electricity price deregulation launch comes later than boiler and turbine replacement dues and ethanol production is considered as an option.

4.4. Results of Scenario-Planning Meeting

Scenario planning meeting was held at a meeting room of Shinko Sugar Mill Corporation in December 26-28th, 2016. Figure 4-7 shows a scene of the meeting. The posters prepared in Chapter 4.3 were used to discuss and concerns, opinions and idea about the scenario were written down on tags. Some outputs are shown in Figure 4-8.

Table 4-2 organizes concerns and countermeasures for each action of the sugar mill. If the bagasse is dried or stored, it may catch fire. Some engineers believe the moisture of bagasse should be kept within some range to avoid fire. Some wetting-induced ignitions in cellulosic materials have been reported (e.g., Gray et al., 2002) and the way of its appropriate management is not clear. The mechanism of bagasse ignition should be investigated and the appropriate storage method should be adopted. Under the current policy, it is difficult for the sugar mill to sell products other than raw sugar, i.e., ethanol, heat and electricity, because the subsidy may be reduced not only in this company but also in other Japanese sugar milling companies in response to the additional income. Separation of division according to each product have to be discussed to start the second, third and fourth business. Regarding the business of selling electricity and its capital investment, the bagasse availability raises the engineers' concern. The amount of surplus bagasse generated fluctuates every year and it sometimes cannot meet with even the internal demand. Increasing the amount of available biomass before launching an electricity business is strongly recommended to overcome their psychological barriers. Importing palm kernel shell (PKS) as biomass resources from abroad can be another powerful option to secure the fuel especially in the early stage. When and how the power company raise the electricity price also weighs on their mind. A negotiation with the power company may facilitate the decision of selling electricity. If electricity is sold in off-season, the mill has to secure the space for the bagasse yard, which is a place for stocking bagasse. Because there is no additional space, the mill has to negotiate with people who have land adjacent to the mill for the space. The space above the public pond, which currently receives the water with the waste heat, can be used as well if the town office permits. As a general concern, they worry about the decrease in sugarcane feedstock in the future. Taking canetop as feedstock may increase the amount of feedstock and alleviate the decrease speed.

Figure 4-7 Scene of scenario planning meeting.

Figure 4-8 Output of scenario planning. Concerns, opinions and idea about the scenarios are written in tags, which are put on blank sheets.

Table 4-2 Actions, concerns and countermeasures for the sugar mill

Action	Concern	Countermeasure
Saving enegy	・Abundant water in process flow	・Development of cultivar that is poor in water
Drying bagasse	・Risk of fire	・Research about the mechanism of bagasse ignition
Ethanol production	・Subsidy for sugar production	・Separating ethanol business
Heat selling	・Subsidy for sugar production	・Separating heat business
Electricity selling	・Subsidy for sugar production ・Stability of the amount of bagasse generated ・Uncertainties about the future electricity price	・Separating electricity business ・Importing PKS from aborad at the beginning ・Negotiating with power company
Storing bagasse	・Risk of fire in bagasse yard ・Space for bagasse yard	・Research about the mechanism of bagasse ignition ・Constructing storage above the river near the mill (Negotiating with the town office) ・Negociating people who have land near the mill to secure space for bagasse yard
Replacement of BPST with CEST	・Capital investment Risk of decreasing feedstock in the future	・Close cooperation with farmers
General actions	・Decrease in engineers ・Decrease in sugarcane feedstock	 ・Taking canetop as feedstock

Table 4-3 organizes concerns and countermeasures for each action of farmers. Because there is little power for the mill regarding the diffusion of high-yielding sugarcane cultivars, they recognized the requirement of additional countermeasures again. The subsidy for sugar production weaken the motivation for famers to choose the high-yielding cultivars because of its low sucrose content, the mill can request the government to change the law so that values are added to the fiber in sugarcane. Another concern from the high-yielding cultivar is an increase in famers' working load. The high-yielding cultivars require harder work in their harvesting than the currently-used one. Considering the aging of farmers and their sufferings in fund shortage, the service of their harvester maintenance would be a strong support. Since the mill can expect additional income thanks to the diffusion of high-yielding cultivars, it should play a role in this support by starting the service such as the lease of harvesters or the dispatch of new labors for farmers. If the high-yielding cultivar is chosen, the working period in the mill would be extended and may overlap with that in other industries. The countermeasure for this problem have not found yet.

The damage to sugarcane crops by frost is one of the general concerns for farmers every year. In Tanegashima, frost is possible during winter and early spring. Because sugarcane is a tropical crop, the sugarcane stem is sometimes killed by the frost. Spraying the hot water from the mill may protect sugarcane from the frost, although the applicable area is limited along the regional heat-transporting pipe.

Table 4-3 Actions, concerns and countermeasures for farmers

Action	Concern	Countermeasure
Diffusion of high-yielding sugarcane	・Uncontrollabitily of farmers' cultivar choice from mill company	
	・Subsidy for sugar production	・Request of changing laws to the government (e.g. Change to law that put values on fiber in sugarcane)
	・Working load for farmers	・Support maintainance of harvester
	・Collision of the extended working period of the mill with other industries such as that of shochu factory	
General actions	・Damage to crops by frost	・Provision of hot water from the mill in winter
	・Decrease in farmers	・Support by mill company (e.g., Investing business that offers technical service for sugarcane farming beginners, or that rents houses for newcomers) ・Hiring foreign workers
	・Expensiveness of harvester maintainance cost	・Support by mill company (e.g., Harvester lease business)
	・Increase in abandoned land	・Start from pasture cultivation, which is easy for beginners to start farming ・Support by mill company (e.g., Investing business that offers cultivation service for farmers who are willing to give up sugarcane farming, or that mediate agricultural recruiting)
	・Land competition with pasture cultivation	
	・Land competition with sweet potato cultivation	
Harvesting canetop and leaf (New idea)	・Unknown relationship between the required amount of canetop and leaf returned to the soil and the soil fertility	・Research about soil fertility
	・Expensiveness of upgrading milling machine for the mill	・Income from other business
	・Current canetop demand from stockbreeding	
	・Current employment of workers in cane cleaning facilities	

Harvesting canetop for increasing feedstock is proposed in Table 4-2. Because some farmers believe that returning canetop into the soil is indispensable to maintain its nutrients, it may not be easy to motivate farmers to hand it over for others. The detailed canetop decomposition mechanism should be studied to support their clear decision.

4.5. Discussion

Through the scenario meeting with the model developed in Chapter 3, it was verified that the actual players can generate a scenario that has not been generated in the viewpoint of either farmers or engineers in the sugar mill. Most measures in the initial scenarios (see Figure 4-4, Figure 4-5 and Figure 4-6) appear to be profitable only for the sugar mill. For example, the sugar mill takes gains from the new business of selling ethanol, electricity and heat. However, they cannot obtain profits without the help from sugarcane farmers. Such situation would be unfair from farmers' point of view but could not be discarded because their support may be a key to the survival of both farmers and the sugar mill in the long run. This is one of the systemic problems in this sugarcane-derived production. The scenario planning using the model enabled them to discuss quantitatively together and to generate the alternative to overcome the problem considering both options. One of the examples is the alternative that the mill starts to lease harvesters to farmers to compensate the lack of their labors. This is the remarkable product that requires both perspectives.

The process model can be used not only for discussion within a sugar mill but also for the communication with other players such as farmers, public servants and researchers. For example, the model can contribute to improving the cultivar-change procedure, the complication of which is one of the concerns as pointed out in Chapter 4.4. Figure 4-9 shows the current procedure for cultivar change in the case of Kagoshima Prefecture, where Tanegashima is located. Currently, it takes almost ten years or over for farmers to change cultivars since agricultural research institute extracts the demands from farmers and sugar mills. Multiple players are involved in several steps, where decisions are made based on their empirical knowledge or feelings. The process model has a potential of clarifying the demands of cultivar from farmers and sugar mills, speeding up of decision making at the committee for registering recommended cultivars and supporting famers' decision on their cultivar choice. Other contributions of the model are related to public and research projects. The feasibility of heat provision from the sugar mill to the regional area has been discussed based on the findings with the process model (JEA, 2016). In addition, the surfactant production process utilizing biomass resources as feedstocks has been under development to seek the new market of molasses-derived bioethanol (JST, 2017). The potential of this process has been discussed partly with simulation-based analyses using the process model.

Through confirming the new role of the model as explained above, it was indicated that the model makes it easy for people in different positions such as engineers, farmers, researchers and public servants to share their common understanding. In this time, the perfect understanding of all decision makers is not necessarily required. Instead, it is required to specify the key players, involve them and arrange the whole related system from the viewpoint of industrial sides. It was also implied that there remains room for plant-derived production to intensify the system without completely uncovering the phenomena.

The problems shown in this case study have not been completely solved yet. Further developments of the model and technology are required for generating more practical scenarios. For example, the model can simulate how receiving canetop as the feedstock will change the mass and energy flow in the sugar mill if additional data is collected. Then, more detailed discussions would be expected on the next scenario planning meeting. Some negotiations with other stakeholders such as the power plant, livestock industries and the policymaker were proposed (see Table 4-2). These stakeholders could also be participants in this meeting for an effective discussion. Modeling and scenario generation should be conducted iteratively. Along this approach, new scenarios will be continuously generated and approach to a practical level.

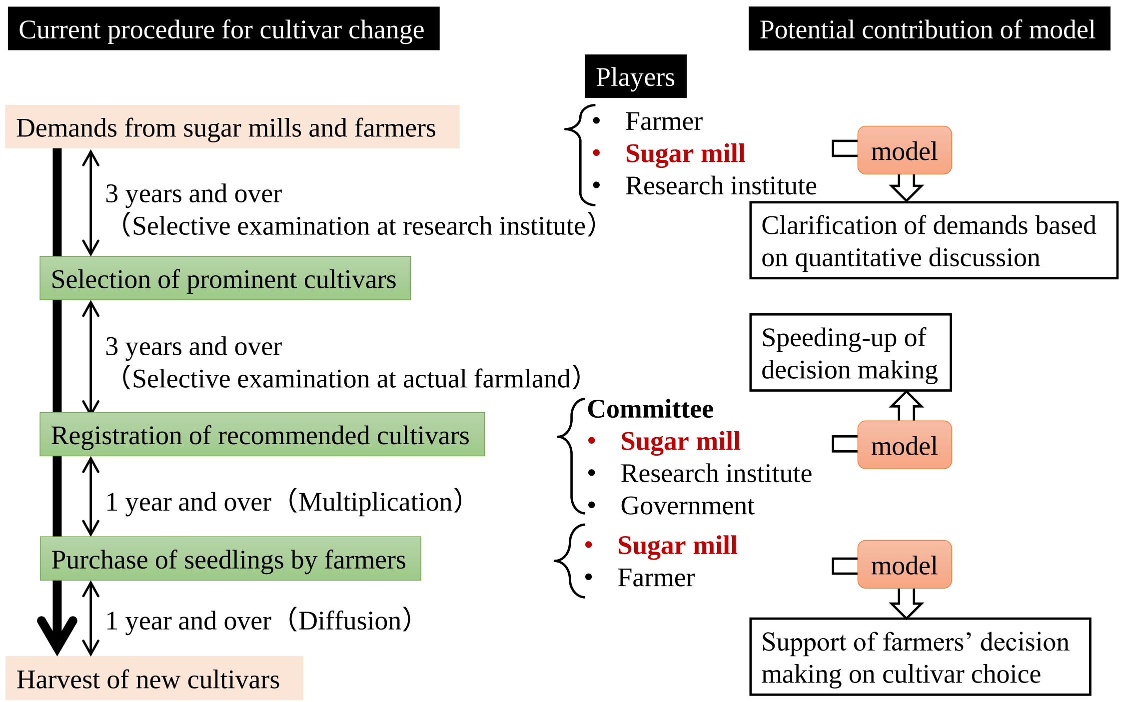


Figure 4-9 Current procedure for cultivar change in the case of Kagoshima Prefecture and potential contribution of model.

4.6. Summary

A scenario planning meeting was held in an actual cane sugar mill to verify the function of the meeting. The present situation of target systems and some possible social change in the future were investigated. Considering the investigation results and using the model developed in Chapter 3, three initial scenario plans were created. These plans were used for discussion among the workers in the meeting. Concerns about the initial scenario plans were picked up and alternatives to avoid them were generated by them through the meeting. Some alternatives were the ones that requires both agricultural and industrial visions. Through the confirmation of such alternatives, the scenario planning meeting was verified as the method of generating alternative scenario candidates.

Chapter 5. Framework of Scenario Planning for Systemic Intensification

5.1. Introduction

Mechanisms of systemic intensification were developed through the case studies in Chapters 3 and 4 in accordance with the concept of systemic intensification proposed in Chapter 2. These are the fruits of the research activity through repeating try and error for finding the way of the systemic intensification. However, it does not follow that actual decision makers can reproduce this activity without the help of researchers, experts and mechanism developers especially in the case of other plant-derived production. As discussed in Chapter 2.3.3, a framework for systemic intensification using above two mechanisms is strongly needed to enhance the practicability. In Chapter 5.2, the activities for planning scenarios for intensifying agriculture and industry in plant-derived production are modeled. In Chapter 5.3, the activity model is verified through being traced by the findings in Chapters 3 and 4.

5.2. Activity Modeling by IDEF0

5.2.1. Activity model

The type zero language of Integrated DEFinition (IDEF0) was chosen as the activity modeling to describe the procedures of systemic intensification. This language has been utilized for the understanding, analysis, and improvement of the target system including things, people, information, process, equipment or materials.

Activities and related elements of the target system are represented by box and arrows as shown in Figure 5-1. Activity boxes are arranged obliquely and named with the number of the order from the top left. Arrows entering the left side of the box are inputs: things and information converted by the activity. Arrows entering the top side of the box are controls: constraints on the activity. Arrows entering the bottom side of the box are mechanisms: information and resources for the activity as necessary. Arrows from the right side on the box are outputs: products of the activity. A model depicted with IDEF0 has a single top-activity named A0. The top-activity can be decomposed into sub-activities A1-An, which can be further decomposed into the next level as necessary. The viewpoint and purpose of the model must be fixed in one model. Actors in the viewpoint conduct the activities. All activities in the model share the same viewpoint.

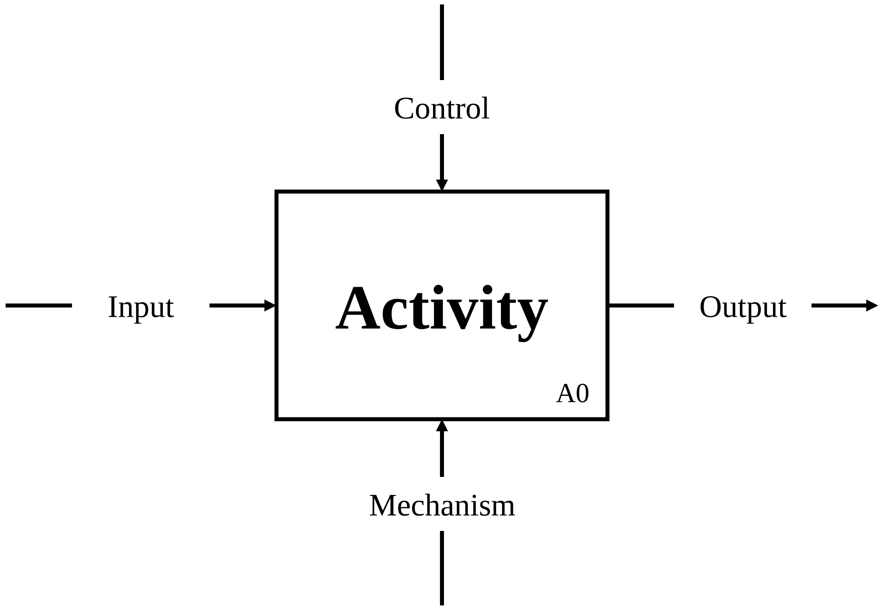


Figure 5-1 Representation of activity and related elements by IDEF0

There are some reports about a framework that has been developed with IDEF0 for systems design. Sugiyama et al. (2008) developed the framework of chemical process design integrating environmental, health and safety evaluation with conventional economic and technical considerations. Uehara et al. (2014) developed a framework of process improvement for risk reduction to support risk management in processes operated in middle-stream industries. The previous frameworks including the above two and the one required in this research should have in common that alternatives can be generated through modeling and simulation. However, these are decisively different in that there are lots of obstacles such as temporal scales and future uncertainties before practicing the alternatives generated as discussed in Chapter 4. Through paying attention to the similarities and differences based on the previous findings, required activities and flows of information between them were logically organized on the activity model.

The top Activity A0: Design intensified agriculture and industry for plant-derived production

Figure 5-2 shows the top activity of the IDEF0 model developed in this study. The viewpoint is defined as a consortium of producers in plant-derived production. This consortium would basically include engineers in industrial sides because they have an ability to manage supply-chain of plant-derived production. In other words, the consortium is well-versed in industrial processes in the targeted plant-derived production. The goal of the activity is to obtain practical scenario plans for reaching intensified agriculture and industry. The technology required for achieving the plan accompanies the output. Through this activity, the roles of both producers and stakeholders become clarified, resulting in outputting players required for carrying out the plan as well. If the consortium failed to generate the above output, they request other decision makers to reconsider the constraints toward the consortium in order to reach a middle ground between them. The activity model can demonstrate the actual procedure of systemic intensification considering individual constraints and available information by them. It should be applicable in all types of agriculture and industry in plant-derived production.

This activity forms a part of Plan-Do-Check-Action (P-D-C-A) cycle. Among P-D-C-A, C-A-P are represented here. It is conducted either constantly as a management project or unusually as an improvement project.

Controls on systems design could be mainly divided into two types of groups: targeted for intensification and other constraints. The former is the present systems and scenarios. The consortium tackled with transforming the present systems and scenarios into the improved ones. The latter is further divided into four types: general constraints, constraints from externals, constraints from internals, and project-specific constraints or evident problems. General constraints are fixed conditions for the consortium and decision-makers who take the outputted request. Geographical features and climate conditions are included in this category. Constraints from externals are determined by the upper decision makers or external ones. For example, available budgets of engineers in the consortium are limited by the company employing them. Products functions should meet existing consumers demand, while process functions such as environmental burdens are regulated under the laws. In addition, the local residents' values such as wish that local traditional culture should be conserved are in these constraints. Constraints from internals are judgement criteria for producers on the viewpoint. Physical aspects of farmers are one of these constraints and directly related to the upper limit of labor for farming.

The last constraint is either project-specific constraints and evident problems, depending on whether the project is on a daily basis or not. If the project is conducted on a daily basis, the project is launched along the given motivations. On the latter case, the project starts to cope with evident problems promptly. Projects from both occasions should be launched to intensify the system.

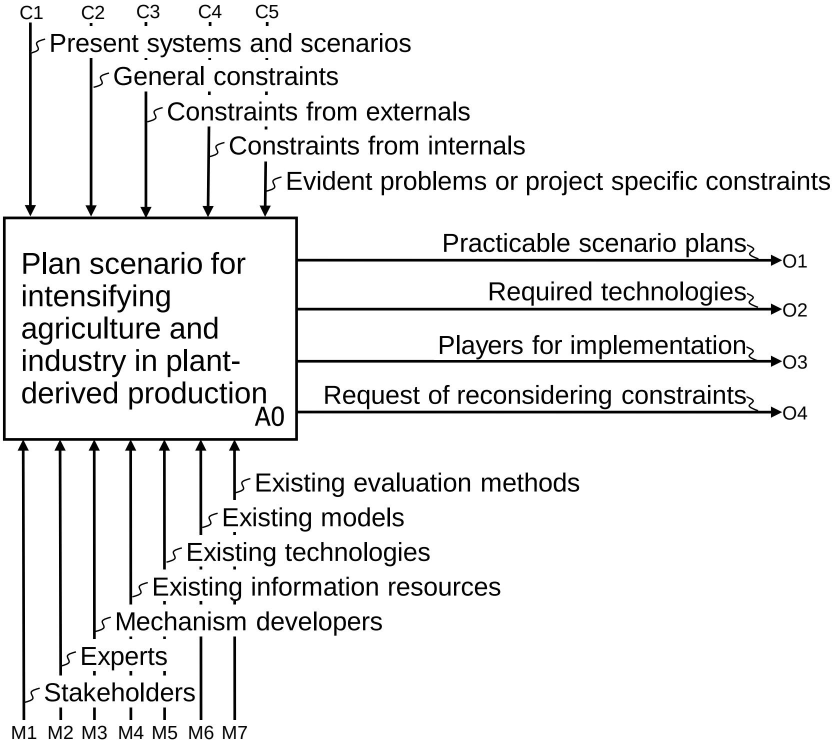


Figure 5-2 Description of the top activity A0.

Several kind of mechanisms are utilized for the output described above under the controls. As is the case in most, plant-derived production is associated with other industries. Stakeholders are involved in this activity as necessary. The consortium consults appropriate experts on their own if some technical knowledge is needed. Mechanisms required for achieving this activity are developed with the help of mechanism developers. Existing information resources, technologies, evaluation methods and models are referred to aid the activity throughout.

A0 Layer: Sub-activities of design intensified agriculture and industry for plant-derived production

Figure 5-3 shows the sub-activities of the activity A0. In A1: manage design of intensified agriculture and industry, external controls should be interpreted and transformed into convenient styles, e.g., project objectives, spatial and temporal boundary, information about present system, and definition of required mechanisms. Abstract external controls are converted into cleared ones that are useful for the following sub-activities. Based on some of the controls provided from A1, present system is evaluated in A2: evaluate present system. A3: generate alternative candidates generates alternative candidates of system so as to surpass the performance of the present system. This is the prominent activity where both agricultural and industrial options are simultaneously considered to search the wider space of alternatives. A4: evaluate alternative candidates, evaluates the alternative candidates generated in A3 according to the way how the present system is evaluated. Although the basic framework in sub-activity A4 is the same as that in sub-activity A2, these are different in the data acquisition stage. A4 requires additional mechanisms to estimate the data. In A5: decide alternative systems, alternative system candidates are screened comparing the present system and the alternative candidates. Finally, A6: plan scenarios, plans scenarios for achieving the screened candidates. Required mechanisms for the above sub-activities are provided from A7: prepare mechanisms.

Spatial and temporal boundary and project objectives output from A1 are shared among the other activities as controls because it contains converted external constraints. As for other outputs from A1, information about present system are the control of A2, while definition of required mechanism are the control of A7. Since outputs from A2, A3, A5, A6, and A7 are controls of A1 and A4 takes an position between A3 and A5, these activities could be iterative procedures and the controls from A1 could be variable. For examples, if failure of deciding alternative candidates are outputted from A5 to A1, spatial and temporal boundary may be updated reflecting the feedback to promote other alternatives generation.

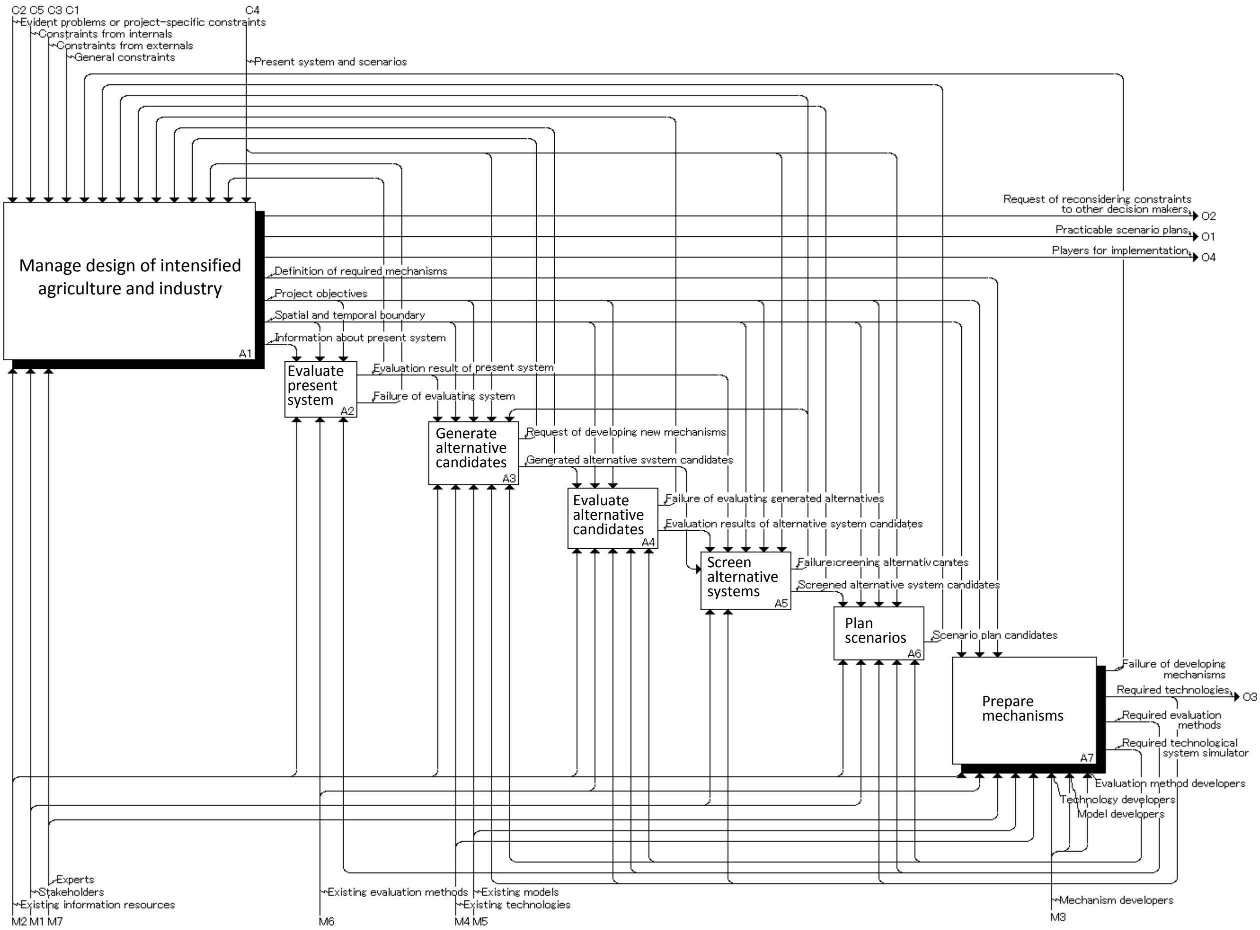


Figure 5-3 Description of the activities of proposed procedure for systemic intensification. Activities A1-A7 are the sub-activities of activity A0.

Since there are multiple interactions between activities of A1 and A7 and other activities, the flow of information remains unclear in Figure 5-3. The sub-activity of A1 and A7 are further developed as shown in Figure 5-4 and Figure 5-5, respectively.

There are five sub-activities in A1 (Figure 5-4). In A11: set project objectives, external constraints are converted into clarified project objectives such as assessment index and the desired standard of system performance. Based on the objectives, spatial and temporal boundary are determined in A12: define system boundary. In A13: scrutinize present system, information about the present system such as data about mass and energy flow in the defined boundary are scrutinized. A4: define required mechanisms for the project, defines required mechanisms based on request of developing new mechanisms and generated alternative system candidates. Through the interactions among A11-A14 and outside A1, scenario plan candidates are obtained. Finally, practicability is judged to output practicable scenario plans in A15: judge alternative systems and scenarios.

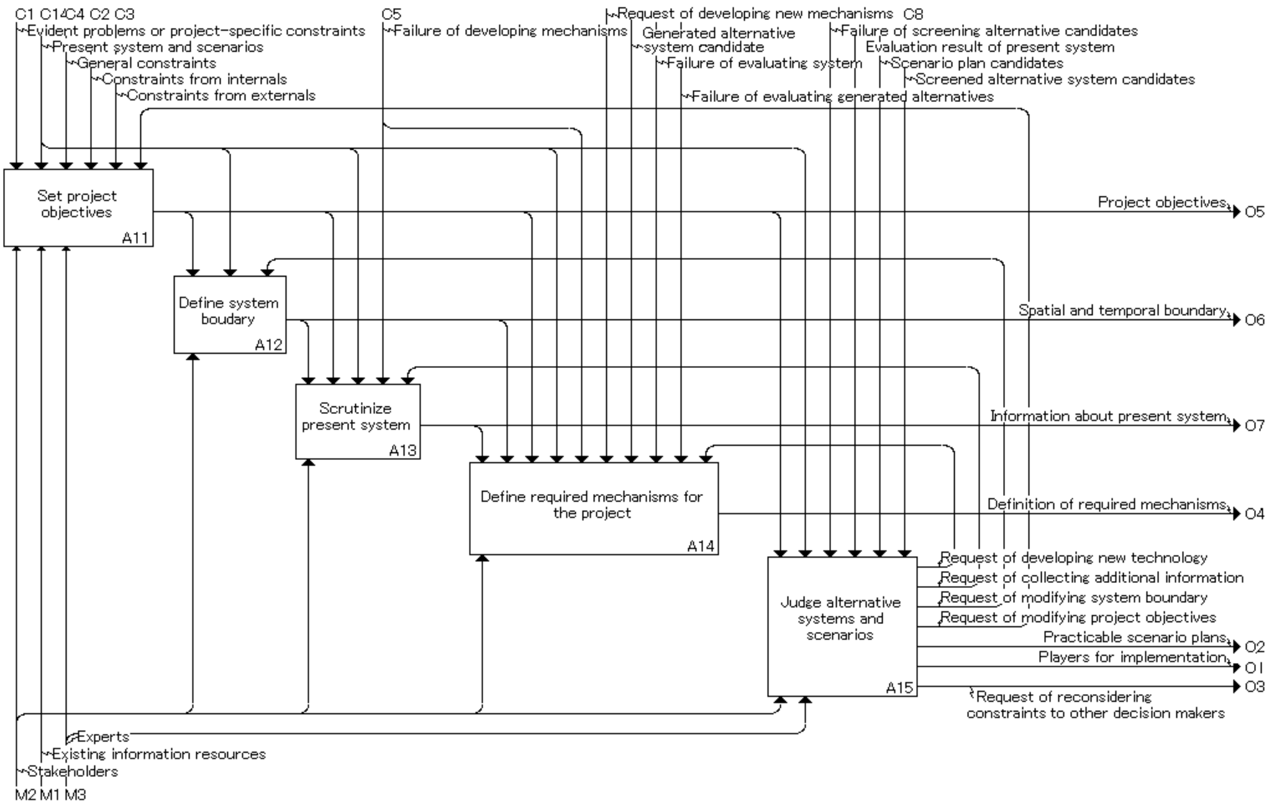


Figure 5-4 Description of the sub-activities of A1. Acitivities A11-A15 are the sub-activities of activity A1.

Figure 5-5 shows the sub-activities of A7: prepare mechanisms. Required mechanisms are specified, under the control of their definition in A71: specify required mechanisms. Existing technologies, models and evaluation methods that meets their definitions are investigated. If there are insufficient mechanisms, request of developing new mechanisms are outputted. In A72-A74: develop technologies, develop models and develop methods, new mechanisms are developed under the control of the requests. These mechanisms are referred again in A71. Specifications of required mechanisms are conveyed to A75: provide mechanisms. Based on the specifications, required mechanisms including existing one and developed one are provided outside A7. If the activity of A71 fails, failure of developing mechanisms are outputted.

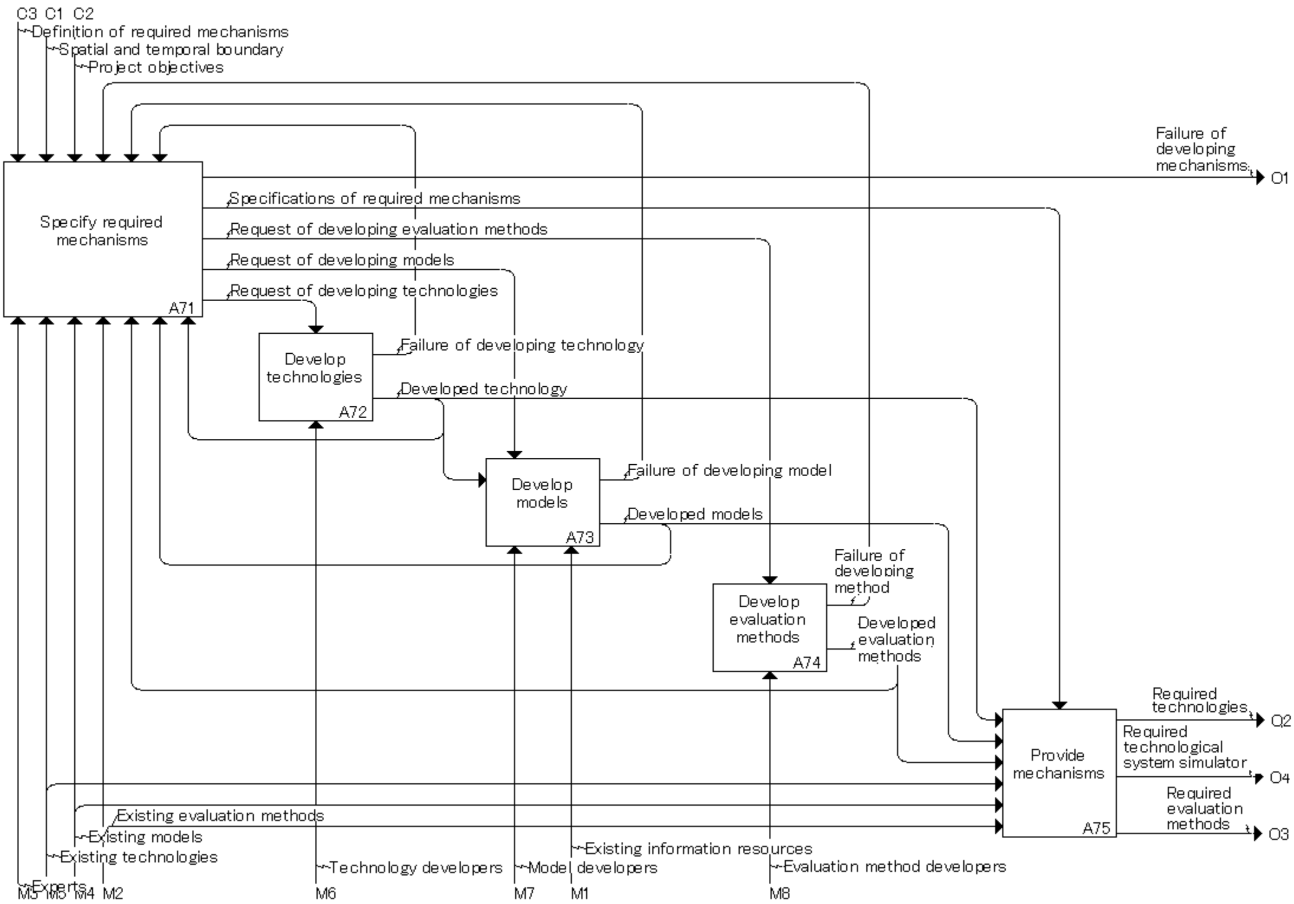


Figure 5-5 Description of the sub-activities of A7. Acitivities A71-A75 are the sub-activities of activity A7.

Looking over the overall picture of the framework, the activity is represented as a hybrid of systematic (A2-A5) and systemic (A6) approaches. The players challenge the limit of a systematic approach by making full use of available resources, while topics in the range over the limit are discussed in a systemic way, that is, not identifying the causal chain exactly. The players can act proactively through A2-A6 without heavily relying on experts and mechanism developers thanks to the provision of mechanisms from A7 when necessary. The framework is represented as an iterative process. The activities seamlessly continue until satisfactory answers or failures are attained.

5.2.2. Case Examples

The applicability of the framework is verified through the tracing for an actual case studies in Chapters 3-4.

In Chapter 3.2, a model is developed and alternatives generation is succeeded considering available options. The viewpoint is a consortium of farmers and a sugar mill. First, increases in raw sugar and ethanol and reduction in GHG emissions are set as a project objective (A11). The system boundary is set as sugarcane processing from cultivation to ethanol fermentation and the temporal boundary is set as 1 year (A12). The present system is scrutinized and the information about the current process flow diagram and mass and energy balance is collected (A13). This information is used to evaluate the present system (A2). While the estimation of raw sugar and ethanol production requires no technical knowledge, no one may know how to evaluate the GHG emissions on site. In this case, failure of evaluating system is outputted to A14, where the definition of required evaluation method is conveyed to A7. Required evaluation method is specified through examining the existing methods and life cycle assessment could be found (A71). This method is provided to A2 via A75 and the GHG emissions is evaluated in this time. Based on the evaluation result, alternative candidates are tried to be generated. The people in the consortium can consider their options such as high yielding cultivar, maceration water flowrate and crystallization times as variables to generate alternatives but cannot obtain the process inventory for them. The requirement of a process model is conveyed to A71 via A14. Because there is no existing process model that can simulate the mass and energy balance of sugarcane processing considering both agricultural and industrial options, the development of a new model is requested to A73. A model developed here is provided for A4 via A71 and A75. Finally, the mass and energy balance of alternative candidates are simulated and used for the evaluation (A4). Comparing the evaluation results of the alternative candidates with that of the present system, competent alternatives are conveyed to A6.

A technology for sugar mills is developed in the existing research and its implementation analysis is conducted in Chapter 3.3. The screened alternative candidates are conveyed to A15 and judged by the consortium. In this time, there remains a concern of an effect of high reducing sugars content on the efficiency of the sugar crystallization process. Further research and development are requested to A14. Existing technologies to meet the requirement are examined but cannot be found in A71. Consulting with experts, a fermentation technology is picked up as a candidate to remove reducing sugars before the crystallization process, and the new technology development is requested to A72. Ohara et al. (2012) developed the technology of selective fermentation (SF) in A72. This technology is incorporated into the model (A74) and provided with the technology together for A3. Alternatives that cultivar changes to KY01-2044 and introducing SF are conducted simultaneously are generated (A3), evaluated (A4) and screened (A5). The screened alternative is judged, but there remains a concern in the return on investment (ROI) of SF. On the other hand, A3 can generate other alternatives that new sugarcane cultivars are developed to enhance ROI of SF and its development is requested to A7 via A14. In the future, new cultivars will be developed according to the new requirement involving sugarcane researchers as mechanisms.

Chapter 3.4 starts from A11, where a power company participate in the consortium as a mechanism. The enhancement of power selling potential without decreasing sugar production is set as a project objective. Evaluation result of the present system (A2) reveals the low potential of selling power in the current sugar mill. Simultaneous implementation of change to a high-yielding cultivar and the replacement of steam turbine in the power plant in the sugar mill is considered as an alternative (A2), but the mass and energy balance in the alternative cannot be simulated. The model is extended to meet the requirement conveyed from A2 via A14 in A7. The alternative candidates are evaluated in A4 and screened as competent ones (A5).

In Chapter 4, the alternative where high-yielding sugarcane is utilized, ethanol is produced from molasses, the current back-pressure steam turbine is replaced with condensing-extraction steam turbine, and surplus heat is sold is screened as an alternative system candidate (A5). Scenarios are planned to achieve the system candidate utilizing information about the future (A6) and scenario plan candidates are outputted to A15. The practicability of the candidate is judged in A15, but there remains concerns. In the future, scenario planning is held again after preparing additional mechanisms or modifying the boundary or project objectives.

5.3. Summary

The framework for systemic intensification was developed on the basis of finding in Chapter 2-4 and proposed as the activity model. The model was depicted from the viewpoint of a consortium including producers in industry who can easily manage the supply chain. Stakeholders are invited to this consortium as necessary. The consortium can start activities motivated by either evident problems or project-specific constraints. With this framework, the consortium can prepare required mechanisms such as technology, model and evaluation method by proactively consulting with mechanism developers, produce a practical scenario plan, develop technology for achieving the plan and encourage the awareness of stakeholders.

Chapter 6. Applicability of Proposed Framework for Systemic Intensification

6.1. Introduction

The applicability of the framework developed through Chapters 2-5 to other plant-derive production is examined in this chapter. Since the framework is developed based on the findings of the case studies on sugarcane-derived production, it is necessary to verify that framework are valid for other cases in plant-derived production. Actual problems and existing works that have found in other plant-derived production are analyzed through two case studies: rice-bran oil refinery (Chapter 6.2.1) and plant factory (Chapter 6.2.2). Appling to these two cases, the general applicability of the framework for systemic intensification is examined in this chapter.

6.2. Characterization of Problems in Agriculture and Industry

To characterize the problems in plant-derived production, the type of relationship between agriculture and industry is sorted as follows. Figure 6-1 shows the group of agricultural crops classified in terms of their utilization. In general, agricultural crops are roughly divided into five types: industrial crops, agronomic crops, forage crops, horticultural crops, and green manure crops. Industrial crops require their conversion into final products in their downstream processes, whereas the others do not. Agronomic crops are staple foods for human beings and main nutrients are starch or sugars. Wheat, potato, and corn are included in this category. Forage crops are ones eaten by livestock such as cows, pigs, horses, sheep, and goats. Agronomic crops in low quality are sometimes consumed as forage crops. Horticultural crops consist of vegetables, fruits and flowering plants. These are sources of fiber, mineral and vitamin or are consumed for entertainment purposes. Green manure crops are plants cultivated for serving as a mulch and soil amendment. They are easily decomposed and can support the growth of other crops for their abundant nutrients.

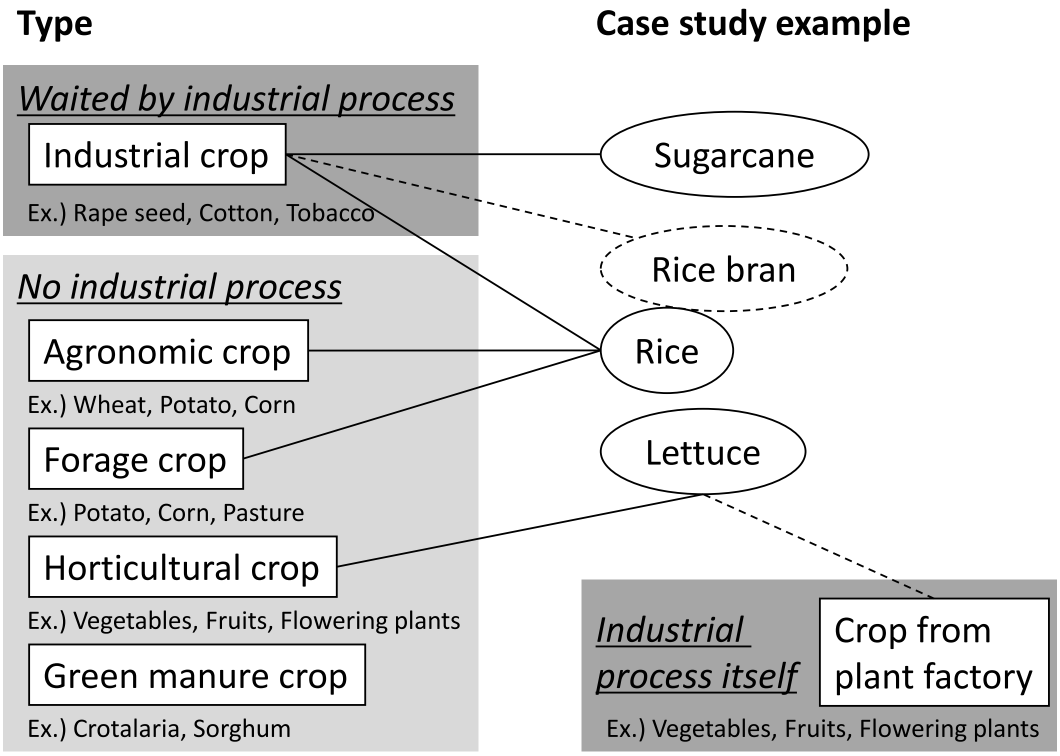


Figure 6-1 Classification of agricultural crops in terms of their utilization

Sugarcane-derived production (SP), rice-bran-derived production (RBP) and plant factory (PF), which are taken as examples of plant-derived production with systemic problems in Chapter 2.1.2, are mapped in Figure 6-1. Sugarcane is classified into industrial crops. Sugarcane in its yielded form is not suitable for eating. Sugar milling processes are required as industrial processes for extracting raw sugar. On the other hand, rice can be classified into industrial crops or forage crops as well as agronomic crops because its usage varies. Some rice is used to produce processed foods such as rice flour, rice crackers and rice cake. Rice in low quality is used for feeding livestock. Some rice bran is either used for producing rice bran oil or disposed of. Because the multiple purposes of rice generate the rice bran in various grades at various places, the rice bran available for the oil production is limited. Vegetables such as lettuce can be obtained from plant factories as well as horticulture, although they are still on a developing stage.

The structure of systemic problems in the three case studies can be distinguished in terms of relationship between agriculture and industry as shown in Figure 6-2. Agriculture and industry are in serial for Type A (SP and RBP), whereas they are in parallel for Type B (PF). Agricultural processes are always followed by industrial processes on the supply-chain of industrial crops in Type A1 (SP).

In this type, both processes are mutually dependent on each other. On the other hand, there may be another type like Type A2 where industrial processes are newly inserted after agricultural processes to utilize unused resources. In this type, agricultural processes are indispensable to industrial processes, but not vice versa. By-products from agronomic crops, forage crops and horticultural crops as well as industrial crops can be candidates of the plant-derived resources for this case. In Type B, agriculture (e.g., open-field cultivation) and industry (e.g., PF) are not on the same supply chain. They are in a competitive relationship as vegetable suppliers.

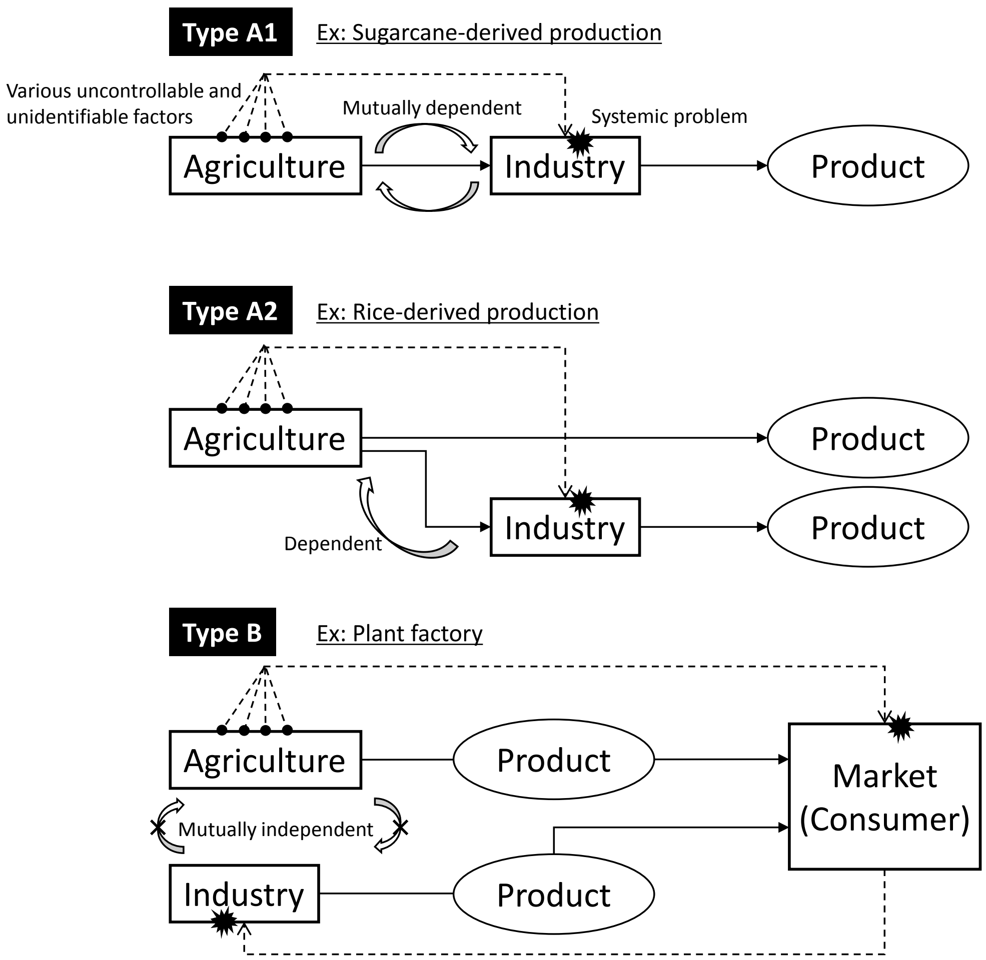


Figure 6-2 Structure of systemic problems in three case studies

Besides the structure of supply chain, the three cases are different in their properties. Table 6-1 summarizes their differences in terms of material, people and money.

Environmental controllability is a unique characteristic for PF. In general, open-field cultivation including sugarcane and rice cultivation is exposed to the outdoor environment such as weather and soils. The control of the environment has sensibly and potentially changed the function of cultivation to the new one as discussed in Chapter 2.1.2.

Table 6-1 Characteristics of sugarcane-derived production, rice-bran-derived production and plant factory

	Sugarcane		Rice		Vegetable	
	Plant	Final product	Plant	Product	Plant factory	Open-field cultivation
Relationship between agriculture and industry	Serial		Serial		Parallel	
Mutual dependence	Mutual dependence		Agriculture is indispensable for industy, but not vice versa.		Plant factory and open-field cultivation are indipendent of each other.	
Objective	Objectives are the same between farming (agriculutre) and sugar milling (industry)		Objectives are the same between farming (agriculture) and rice milling (industry) but different between rice bran refinery and them		Objectives are the same between plant factory (agriculture) and openn-field cultivation	
Production scale	Depend on supply (sugarcane farmland)		Depend on supply (availabe rice bran)		Depend on demand (market), but flexible	
Exposure to climate	Affected	-	Affected	-	Almost not affected	Affected
Main product	Sugarcane	Raw sugar	Rice	Rice straw	Vegetable	Vegetable
By product		Molasses (or Ethanol) Bagasse (or Electricity)		Rice husk Rice bran (RBO, oleo-chemical)		
Harvest cycle	Once per 1-2 years	Winter	Once or twice a year	Almost continuos	Continuous	Limited season
Temporal constraint	Sugarcane should be milled as soon as possible		Rice bran should be processed as soon as possible if oil is produced		Vegetable should be consumed as soon as possible but it lives longer	
Producer	Farmer, Sugar mill		Farmer, Rice bran oil industry		Entreprenuer	
Monetary aspect	Subsidy to sugar production	Subsidy to sugar production		Waste cost or income from value-added production		Subsidy to open-field cultivation

The current main product of SP is raw sugar. Molasses and surplus bagasse are regarded as byproducts in Japanese mills, but they can be converted into ethanol and electricity, respectively. On the RBP supply chain, white rice is the main product and rice straw, husk and bran are regarded as byproduct. Some rice bran is refined into rice bran oil, oleo-chemicals and other value-added products such as Inositol and Phytin. The product of PF is vegetable alone. All cases produce foods, while SP and RBP produce inedible products. The characteristics of intermediates (plants) also differ in their temporal constraints.

Sugarcane is harvested once per one or two year (see Chapter 3.2.3) and rice is once or twice a year. The seasons of harvesting them are restricted by regional climate conditions. From the viewpoint of factories, sugarcane should be milled as soon as possible after harvesting because its sucrose begins to be decomposed into reducing sugars. Because there is no cost-effective way to keep sugarcane fresh, the working period of sugar mills is limited in the harvest season. Rice bran also begins to degrade after polishing. Nevertheless, the working period of rice-bran-oil refinery is not completely restricted by this degradation because brown rice can be preserved for years and is milled throughout the year: White rice is usually purchased by consumers as they can consume before its expired date considering its easier degradation compared with brown rice. The term of consumption is relatively short for vegetables from PF (although it depends on the kinds of vegetable) but is longer than that from open-field cultivation (see Chapter 2.1.1.c). While the life of the final product from PF is limited within several weeks, that raw sugar from SP and rice bran oil from RBP can be preserved more than a year.

Comparing potential players among the three cases, there are people in both agricultural and industrial sides for SP and RBP, although there may be additional stakeholders such as livestock industries, power plants, compost makers, new oleo-chemical consumers, etc. On the other hand, the roles of agricultural and industrial sides are integrated into one role as producers in PF case. They should have both cultivation and plant operations skills. As stakeholders of PF, open-field cultivation farmers, markets and consumers may be involved.

Regarding monetary aspects, SP and PF are associated with subsidies in a different way. Since the main product of SP has been raw sugar, which is important for assuring national food security, some subsidies have been distributed to farmers and cane sugar mills according to their contribution to the sugar production. In contrast to SP, PF has not taken subsidies although they have been given for open-field cultivation. PF has been regarded as factory instead of farmland. This subsidy differentiation has prevented the introduction of PF. Unused rice bran is currently regarded as waste and requires waste disposal cost. However, the cash flow may be reversed if rice bran is used for value-added production.

How these differences in the properties influence on the actual activities in the framework developed in Chapter 5 are discussed in the following section.

6.2.1. Case Study on Rice Bran Oil Refinery

The framework developed in Chapter 5 was applied to RBP case. The viewpoint of this case is set as a rice bran oil refinery because the supply chain can be managed from this viewpoint. The location of the refinery and the speed of rice bran deterioration is included in general constraints. Quality and quantity of existing products and their stability are constraints from consumers, while the odor regulation is a constraint from the law and the residents around the refinery. If the refinery regards rice bran as waste from rice production, the workers may have a sense of mission that their work supports rice production. This mission is categorized into internal constraint. According to the on-site investigation by Muta (2017), some factory suffers from the treatment cost for waste water that contains abundant phosphorus. This problem is included in evident problems. Some factories are trying retrofit design of the current factory for more efficient and additional value-added production because it has been developed on ad hoc design (Muta, 2017). This motivation is categorized into a project-specific constraint. In spite of these evident problems, the utilization of unused rice bran is not necessarily motivated. However, the refinery can start the activities by setting objectives of utilizing unused rice bran for the business expansion or corporate social responsibility (A11).

The effective utilization of unused rice bran generated in rice mills has been challenging only with the effort of rice-bran-oil refineries because of its unstable quality and decentralized generation. The collaboration of rice mills is required to change the location and the timing of rice polishing.

However, they have been hardly motivated to care the quality of rice bran because its disposal cost has not necessarily critical to the business continuity, although they are waiting for the chance to sell it at higher price in a passive attitude. This is why the location and the timing of rice polishing have been determined only by the white rice market. A tool for analyzing the performance of rice-bran-derived production is required to give an incentive for rice mills to care the value of rice bran. The activity should be started from the rice bran refinery alone at the beginning.

Based on the above objectives, Muta (2017) set a system boundary as life cycle of rice (A12) and scrutinized the present rice-bran-derived production (A13). Existing rice-bran oil refineries were modeled to generate alternatives for achieving the objectives (A7). The overview of the model developed is shown in Figure 6-3. LCA was conducted using this model and the LCA database of IDEA (JEMAI, 2016) to evaluate GHG emissions. Some alternatives reduce GHG emissions by introducing cogeneration facilities into the factory. Recently, a technology for recovering phosphorus in the waste water has been developed (e.g., Sakamoto et al., 2017). Incorporating this technology into the model (A7), additional alternative generation would be expected. In general, agriculture is one of the largest consumer of the limited resource of phosphorus (Matsubae et al., 2011), which mainly comes from fossil resources. Because rice is produced in great amount in many countries, an appropriate introduction of such technology with the utilization of the unused rice bran could greatly contribute to the sustainability of agriculture. Through these existing works, some activities in the framework have been verified in the case of rice bran oil refinery.

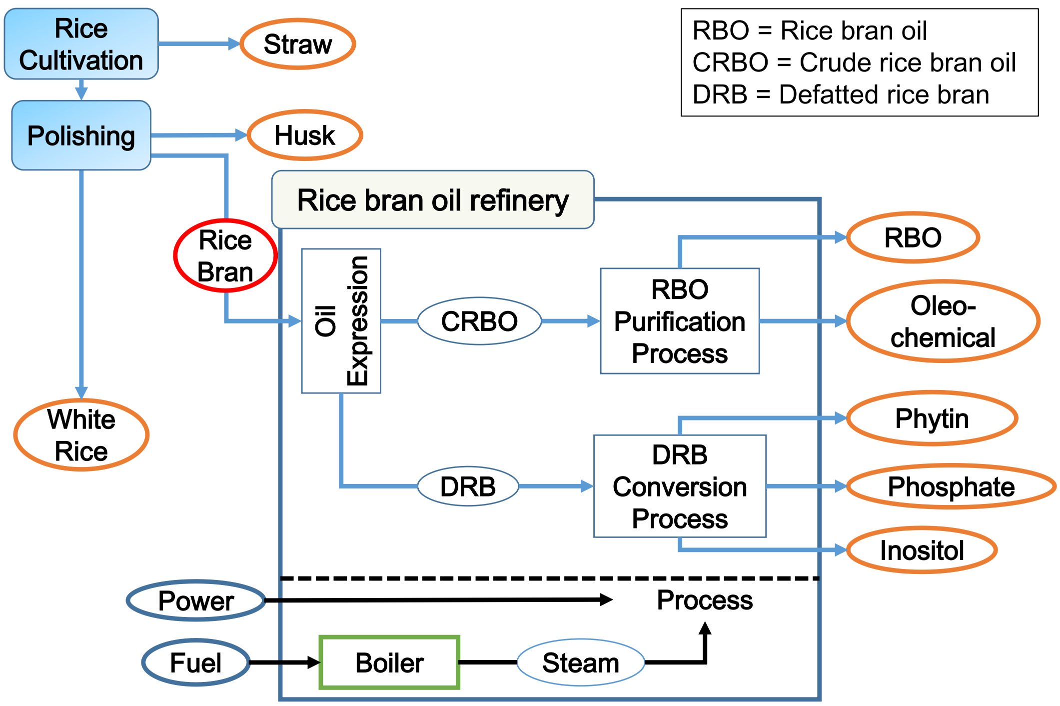


Figure 6-3 Life cycle model of rice bran (modified from Muta, 2017)

The major difference between SP and RBP is the difficulty in inviting people in the agricultural side into the viewpoint because the business in the industrial side is not necessarily critical to them. However, the activity can be initiated from the motivation of the industrial side. Modeling the existing refinery processes and technologies can make the people in the agricultural side recognize the value of utilizing rice bran based on a quantitative discussion, evolving into more profound one.

The stakeholders should be invited into the consortium in order nearest to the industrial processes for the smooth discussion. In RBP case, rice mills are invited first because there is room for improvement among them with rice-bran-oil refineries. As described above, the design parameters determined by rice mills such as their location and timing of rice polishing have great impacts on the oil-extraction efficiency. After the sufficient discussion between them, farmers are invited to seek other alternatives by considering their options such as cultivar choice with industrial options. Once the consortium comprised of both agricultural and industrial side could be established and the project objective could be shared among them, the activities would progress as with SP case. The configuration of the activity model developed based on SP does not change in RBP, but the iteration of sub-activities may increase to prepare mechanisms for motivating stakeholders.

Just because the framework is applied to this case, it does not necessarily follow that unused rice bran becomes immediately available for the industrial use. However, once the mechanisms such as a process model, evaluation methods and related technologies are developed, agriculture and industry in rice-derived production would be easily adapt to the new social or environmental conditions in a coordinated manner.

6.2.2. Case Study on Plant Factory

The framework developed in Chapter 5 was applied to PF case. The viewpoint of this case can be set as entrepreneurs for starting the PF business. The quality and quantity of vegetables and the stability of their production for the existing consumers are categorized into the external constraints but entrepreneurs are somewhat free from these constraints because they can choose the location and production scales to construct a new factory. Internal constraints may be characteristical among the three cases. They may have a strong entrepreneurship unlike the other two cases. There are some evident problems of the low competitiveness of vegetables from PF in the existing market compared with those from open-field cultivation. Lack of knowhow about the detailed design of PF is also added to the evident problems. Vegetable consumers who wish securing their food securities and the society which promotes environmentally-friendly agriculture.

The case where PF entrepreneurs alone cannot take a measure under the situation that open-field cultivation accounts for most of the market is assumed. Those who suffer a disadvantage from this situation are consumers, but it is not rational to motivate them to buy vegetables at higher price from PF in preparation for their food security. Although the government should intervene in the market for the public good, they have no way to determine how preferential treatment should be given to PF. The consortium can involve PF entrepreneurs and policy makers.

The PF should be designed considering the climate conditions, the supply from open-field cultivation and the demand of vegetables, and technology options. However, existing PF has been designed without analyzing the mass and energy flows in detail. In fact, there remains room for improvement in the current PFALs (Maruo, 2015). This is partly because it is difficult to quantitatively discuss the complex phenomena of plant growth mechanism, which has been discussed within the agricultural field.

Tominaga (2017) has applied a simulation-based analysis to the design of plant factories. In her work, system boundary was defined as one PF (A12), the actual PF was scrutinized and the information including design parameters was investigated (A13). Because a mechanism for generating alternative was in short, a process model was developed using the information (A7). The overview of the model is shown in Figure 6-4. The work and heat absorption of the air conditioners, heat transfer through the wall and heat generation from workers' and plants' bodies and the apparatus including air conditioners and lighting equipment were simultaneously modularized in one model. Using this model, some alternatives were generated (A3) and evaluated (A4). The evaluation results indicated that the most energy-efficient or environmentally-friendly design such as the width of wall varies depending on the local climate conditions (A5). Through these existing works, some activities in the framework have been verified in the case of PFs.

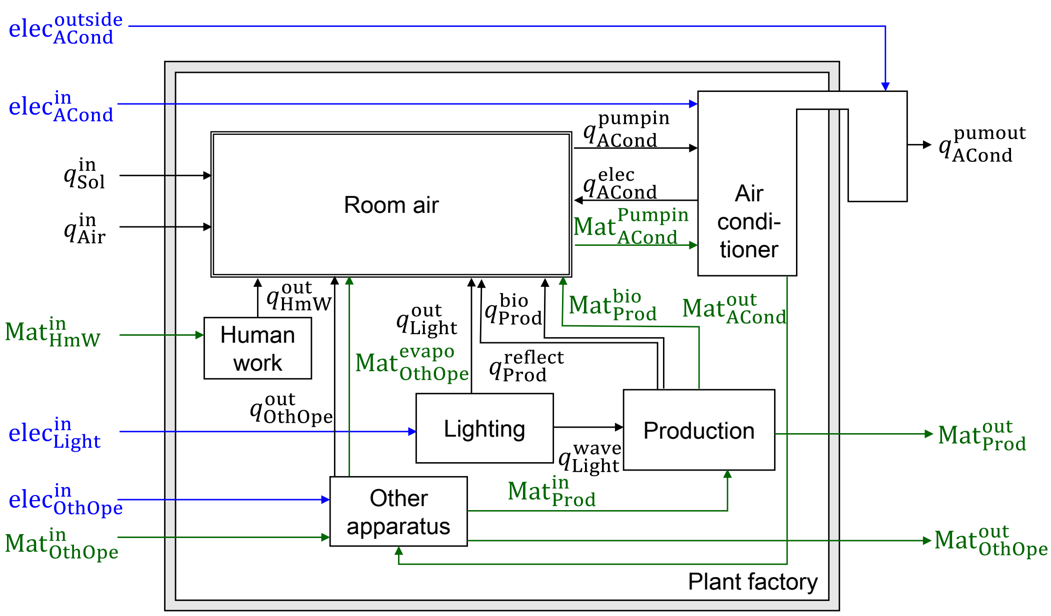


Figure 6-4 Energy balance in the modeled plant factory (modified from Tominaga, 2017)

The modeling approach might be helpful for further discussions with technology developers. Vegetables that grow larger in the fixed period have been preferred in open-field cultivation because the planting and harvesting seasons are fixed for their seasonality. However, design parameters will change in PF. The largeness of them becomes a fixed parameter, while the period of vegetables growth becomes a variable parameter which the breeding technology determines. In addition, vegetables in PF do not need high resistance toward storm, insects and diseases as those in open-field cultivation do. In other word, the requirements on resistance of cultivar will be loosen and the technology developers can concentrate on shortening the growth period. If the data related to these parameters are collected and the relationship among them are modeled, more detailed discussion would be possible. Through such modeling approach, the space for alternatives of cultivars could be widen. This logic is in common with that in SP case, where the new guideline for sugarcane cultivar is generated with through modeling selective fermentation technology (see Chapter 3.3.4).

The case study of PF has unique characteristic in the competitive relationship between agriculture and industry (see Figure 6-2). PF and open-field cultivation are mutually independent. Therefore, stakeholders who can participate in the consortium in this case are different from the other two cases: people in the agricultural side are excluded from the consortium. The design and given parameters are also different. While the agricultural options are set as design parameters in the former two cases, those in open-field cultivation are regarded as given ones in PF case. Nevertheless, the configuration of the framework developed in Chapter 5 does not change.

Through the discussion based on a modeling approach, the intrinsic market value of vegetables from PF and its desirable production scale will be discussed considering the food security. As a result, new alternatives and discussion for practicing them could be expected. For example, the introduction of PF could be facilitated by making consumers partly bear an insurance fee for protecting their food security.

6.3. Applicability and Limitations

The applicability and limitations of the framework is discussed based on findings through the case studies of SP, RBP and PF. Table 6-2 summarize the difference between three types of plant-derived production.

Table 6-2 Summary of difference between three types of plant-derived production

Type	Driving force	Uncertain parameter	Controllable parameter (except for industrial parameter)
A1	Agriculture and industry	Social change, Climate	Agricultural option
A2	(Agriculture and) industry	Social change, Climate	Agricultural option
B	Industry and other than agriculture	Social change, Overall agriculture	Other than agricultural option

Plant-derived resources in the same group in Figure 6-2 have common logical structure of systemic problems. For example, production systems from industrial crops such as oil plants, coffee and rubber are categorized into Type A1. A number of uncontrollable and unidentifiable factors in the agricultural processes affect the efficiency in the industrial processes for all these cases. As long as both processes are in series, there is a possibility of giving rise to systemic problems as is in SP case. Because both processes are mutually dependent on each other as mentioned in Chapter 6.2, driving force for systemic intensification could be obtained from both sides.

There may be unused plant-derived resources that are expected for the industrial use like rice bran. These resources are categorized into Type A2. As discussed in the case study of RBP, it is difficult to obtain the driving force from agricultural side, because agricultural players are generally indifferent to the industrial processes. The framework could be applied to such a case if the stakeholders could be motivated accordingly.

The logical structure of systemic problems in Type B may be only applicable to PF case as long as an innovative technology which produces crops in parallel with open-field cultivation will emerge in the future. Because agriculture competes with industry, no driving force can be obtained from agriculture. Instead, other stakeholders such as consumers and policy makers may have motivation to collaborate with industry.

Although the motivation of people especially in the agricultural side, driving force for systemic intensification and controllable parameters are different among the three types, they can commonly generate new alternatives through modeling and simulation and may require scenario planning for overcoming the temporal gap and future uncertainties. In other words, the framework has a potential of contributing to systemic intensification of agriculture and industry in various types of plant-derived production.

While the framework is applicable to wide range of plant-derived productions that are related to industrial processes, the instances of the four concepts, i.e., input, output, control and mechanism, vary depending on cases. The controls and mechanisms of the top activity are compared in Table 6-3. Because these instances are totally different from each other, the project managers should carefully specify them.

Table 6-3 Differences in control and mechanism of the top activity among the three examples of plant-derived production

Viewpoint	Cane sugar mill	Rice bran refinery factory	Plant factory entrepreneur
Control			
Evident problem	Prospects of future bankrupcy Unstable production		Difficulty in implementation of plant factory Difficulty in process design
Project-specific constraint	Increase in revenue Reduction of business risk	Increase in revenue Reduction of business risk	Obtaining revenue Reduction of business risk
Constraints from external	Quality and quantity of final product Stable sugar production Bagasse supply for livestock industries	Quality and quantity of final product Stable rice bran oil and oleo-chemical production	Quality and quantity of final product Stable vegetable production
Mechanism			
Stakeholder	Society: Desire for reduction in environmental burden Power consumers: Desire for energy security Desire for reduction in electricity prices Sugar consumers: Desire for increase in food security	Society: Desire for utilization of unused rice bran	Society: Desire for reduction in environmental burden Vegetable consumers: Desire for increase in food security

The availability of existing resources such as information resources, models and evaluation methods varies depending on cases. For example, there seem abundant data and technologies on agronomic crops such as wheat, rice, potato and corn over the countries because it is greatly worthwhile to study them for feeding the people. The resource availability strongly influences on the work efficiency of activities in the framework. If a mechanism for some activities is insufficient, a new mechanism should be developed with mechanism developers via A7 (see Figure 5-3), consuming additional costs. In addition, the resource availability determines the limitation of discussion. There is a risk that the players cannot obtain a satisfactory scenario plans under the budget and time allowed because of the shortage in the resources.

6.4. Summary

The applicability of framework that have been developed based on the findings in sugarcane-derived production was examined in this chapter. Rice-bran-oil refinery and plant factories were chosen as case studies for applying this framework. There were some remarkable difference in the structural, material, human and monetary aspects between sugarcane-derived production, rice-derived production and production from plant factories. The instances of controls and mechanisms were also different among the three cases. Nevertheless, all activities in the existing works about these cases could be included in the framework. Through these examinations, the applicability of the framework to other plant-derived production were partly verified. The accumulation of case studies of scenario planning meeting is needed to verify the applicability overall.

Chapter 7. Conclusion and outlook

7.1. Conclusion

This thesis presented the concept of systemic intensification as a systems design method in plant-derived production through untangling systemic problems. Actual problems were analyzed to examine the required concept of the systems design. Based on the analysis, these problems were attributed to three challenging derived from differences between agriculture and industry: difficulties in recognizing and analyzing the problems and in building consensus among stakeholders. To tackle with these challenges, three following mechanisms that should be provided in design stages were proposed for systemic intensification: a model that can analyze agriculture and industry in an integrated manner, a method to plan scenarios considering time scales and future uncertainties and a framework for actual decision makers to utilize the model and method practically. Through case studies on sugarcane-derived production, these mechanisms were verified and the framework was developed based on the findings. In addition, the general applicability of the framework was partly verified based on case studies on rice-bran-oil refinery and plant factories. Finally, with the framework developed in this study, the decision makers in plant-derived production would prepare mechanisms through proactively involving mechanism developers, produce a practical scenario plans, develop technology for achieving the plan and encourage the awareness of stakeholders.

Plant-derived production has sometimes faced systemic problems, which cannot be attributed to causes and that one decision maker cannot solve, and, therefore, has been prevented from fulfilling its potential. In such a situation, this concept of systemic intensification would play an important role in getting over the problems. Systemic intensification offers the method for overcoming the gap, helps the actual decision makers widen their scope and support the decision makings for intensifying agriculture and industry. Such framework enhances the resilience of agriculture and industry. They will be more flexible to social changes or technological progress than ever.

7.2. Outlook

This thesis generates the following recommendation for future studies.

Simplification of activities in the framework

The framework developed in this thesis is strongly constrained by data availability especially in agriculture and sometimes requires many tedious steps to reach a final outcome. On the other hand, there remains plentiful pieces of knowledge inside the farmers' brains that cannot be shared with others. Considering the farmers' aging in some countries, some precious knowledge may be lost in several decades. The structuration of such knowledge should be conducted as a future study to compensate the shortage of available data, reduce uncertainties in the model, and promote to generate more variety of alternatives.

Automation of generating scenario alternatives is another contribution to the simplification. A scenario planning meeting consumes time for involving other stakeholders and being accompanied by trial and error. Currently, the automation of scenario generation driven by model is technically difficult because of the calculation time. The enhancement of computer processing capacities is desired.

Sound support of farmers' decision

The ratio of independent business to corporation business in farming depends on regions and countries. Independent farmers account for the most of the farming area in Japan. In this case, it is rather difficult to organize a number of independent farmers for systemic intensification. From the viewpoint of other stakeholders, farmers' decision may look uncertain, even if consensus were built among them in advance. In addition, it is not practical to invite all farmers if the ratio of independent farmers is considerably large. Moriizumi (2017) considered that cassava farmers in Thailand lack intrinsic motivation for breaking down their present uncomfortable situation even if they have an awareness of the problems and better solutions. She also remarked that recognizing the real values of their crops and nursing their self-esteem are keys to motivating their actions. An additional research is needed to specify what factor is associated with their motivation by collaborating with other academic fields such as behavioral economics.

Way of responsibility assignment

The framework developed in this thesis is premised on the integration of viewpoints of multiple decision makers such as farmers and engineers and may cause a paradigm shift about responsibility for the products. In the case for sugarcane-derived production (see Chapters 3 and 4), sugarcane farmers will have to be responsible for the ethanol, electricity, heat as well as raw sugar the sugar mill produces because increases in those products are partly attributed to them. Rice farmers may be responsible for rice-bran-derived products whereas vegetable consumers who want to secure the food security may have to support plant factories to enter the market (see Chapter 6). There remains questions of how each decision maker should take responsibility for the value and supply chains they engage in. One remark related to this discussion is represented in Chapter 3.2.5, where how the GHG emissions should be allocated to each product. Life cycle thinking would be a strong approach to finding the answer.

Expansion of Scope of Application

While the applicability of the framework developed in this thesis is not verified for all plant-derived productions. An activity of planning scenario is not verified in the case of rice-derived production and plant factories (see Chapter 6). In addition, there may remain some characteristical cases that have not yet discussed in other plant-derived production. The accumulation of case studies is needed to make this framework more generally applicable.

The application to forestry-derived production requires further research and discussion. The structure of problems in agriculture and forestry is largely in common. Forestry is influenced by climate conditions, soils and other natural factors as agriculture is. The difference in temporal scales between forestry and industry is greater than that between agriculture and industry. Some simulation-based approaches have been applied to systems design (e.g. Kanematsu et al., 2017b) as have been done in this framework. However, the overall framework cannot be applied to forestry-plant-derived production because of its critical differences: the absence of stakeholders at present. In general, forest has the time-scales of decades, which sometimes go over the generation and are larger than human life-span. On the other hand, the framework in agriculture-plant-derived production has been developed on the assumption that stakeholders can communicate with each other. Further research is needed to develop the framework that can apply to forestry-included systems design.

Development of key performance indicator

It is sometimes difficult to motivate players to utilize the framework if there is no evident problems like the case of rice-bran-derived production. In such a case, the activity should be initiated under the control of project-specific constraints in their daily work. To make them recognize the necessity of the framework for systemic intensification, some key performance indicators that represent the degree of intensification are required.

Application of the framework to other systems design

This framework will strongly support the design of energy systems in the upper scale of plant-derived production. The contribution of cane sugar mills to the energy security in islands with the support of the simulation is one example (see Chapter 3.4). Simulation-based analysis has played an important role in the systems design of the national (Kikuchi et al., 2014) and regional scales (Kikuchi et al., 2016b), where the amount of available plant-derived resources has been regarded as fixed parameters. However, these parameters could be variable with this framework and the space for alternatives in national or regional systems design would be widen by connecting these researches. It would promote industrial symbiosis in rural areas that encompass both agriculture and industry (e.g. Kanematsu et al., 2017a), in particular.

Notation

Symbol

a_n = Quadratic coefficient of sugar yield equations in the *n*th crystallization

Af = Farmland area, ha

adj = Application amount of pH adjusters, 10^3 kg ha^{-1}

alk_q = Application amount of alkaline material, 10^3 kg ha^{-1}

ams = Ammonium sulfate demand of yeast culture tank, kg

b_n = Linear coefficient of sugar yield equations in the *n*th crystallization

$bcmp$ = Boiler compound consumption through the whole processes, kg

bd = Bagasse demand for combustion, 10^3 kg

bur_k = Removal rate of part *k* by burning before harvesting, kg kg^{-1}, *k* = top, leaf

bxo_q = Goal of brix content in material *q*, kg kg^{-1}

BC_m = Base cost of machine *m*, JPY

c_n = Constant term of sugar yield equations in the *n*th crystallization

c_j = Heat capacity of stream *j*, kJ kg^{-1} K^{-1}

chd_m = Chilled water demand of machine *m*

$clag$ = Cleaning agent consumption in precipitation, kg

cld_m = Cooling water demand of machine *m*

cro = Selected cropping type

cul = Selected cultivar

cyl = Cylinder oil consumption of roll mills, kg

$C_{j(k)}^{i}$ = Content ratio by weight of component *i* (in part *k*) in stream *j*, kg kg^{-1}

$C_{\mathrm{sat}}(T)$ = Saturated concentration of sucrose at temperature *T*, kg kg^{-1}

$C0^i$ = Potential content ratio by weight of component *i* in sugarcane, kg kg^{-1}

CM = Capacity of cane sugar mill, 10^3 kg d^{-1}

CS = Estimated sucrose composition in stems of yielded sugarcane, %

$CS1$ = Lower end of protection range of sucrose composition, %

$CS2$ = Upper end of protection range of sucrose composition, %

CT = Time for selective fermentation in one cycle, h

CY = Concentration of yeast weight in volume basis, kg L^{-1}

$d_{pp,pp'}$ = Distribution ratio from subprocess pp to subprocess pp', kg kg^{-1}

D = Diameter, m

DF = Distribution ratio for determining sugarcane price assigned to farmers' contribution, kg kg^{-1}

D_n = Drain water from *n*-th evaporator, kg

D_s = Drain water from low-pressure steam, kg
DE = Ethanol in Drain 1, kg
DY = Durability of yeast, d
ebt = Brix extraction rate from cane tops and leaves in milling process, kg kg^{-1}
ebs = Brix extraction rate from stem in milling process, kg kg^{-1}
ed_m = Electricity demand of machine m, kWh
ess = Sucrose extraction rate from stem in milling process, kg kg^{-1}
f_l^i = Growth index for content ratio of component i in stem by farm operation l
fca_q = Conversion factor of alkaline materials q into calcium carbonate
fcr^i = Removal rate of component i from cane juice to filter cake in the clarification process, kg kg^{-1}
ff_l = Growth index for stem weight by farm operation l
fph = Coefficient of final soil pH to lm, pH (kg $ha)^{-1}$
frz_f = Application amount of fertilizer f, 10^3 kg ha^{-1}
$F_{j(k)}^i$ = Flowrate of component (i in part k) in stream j, 10^3 kg ha^{-1}
$F_{j(k)}$ = Total flowrate (in part k) in stream j, 10^3 kg ha^{-1}
$F0$ = Potential output for chosen cultivar, 10^3 kg ha^{-1}
FA_j = Annual total mass flow of stream j, 10^3 kg $year^{-1}$
FC_j^i = Total weight of component i cultured in one cycle of yeast culturing, 10^3 kg $batch^{-1}$
Fh_j = Total mass flowrate of stream j, 10^3 kg h^{-1}
FM = Maximum value of sugarcane yield per hectare, 10^3 kg ha^{-1}
FV = Volume of liquid, kL
Gr = Grashof number
h' = Coefficient of heat transfer, W m^{-2} K^{-1}
$h_q(T)$ = Standard enthalpy of formation of q, MJ kg^{-1}
hd_m = Demand for high-pressure steam of machine m, MJ
hv_k = Removal ratio of part k in harvesting process, kg kg^{-1}
hw = Selected harvesting technique
H_q = LHV of material q, MJ (10^3 $kg)^{-1}$
ir = Irrigation amount, mm day^{-1}
IFR = Income per farmland area per year for farmers, JPY ha^{-1} $year^{-1}$
IFC = Income per farmland area per year for factory, JPY ha^{-1} $year^{-1}$
IM = Maximum limitation of irrigation amount, mm day^{-1}
j_H = Heat transfer factor
la = Slaked lime addition rate to cane juice in clarification process, kg (10^3 kg $juice)^{-1}$
$lcas$ = Cascaded low-pressure steam from power-conversion turbine, MJ
ld_m = Demand for low-pressure steam in machine m, MJ
Lt = Tube length, m

Ls = Stream length, m

mc = Ratio of molasses attached to the crystal nuclei after centrifuging third massecuite in the crystallization process, kg kg^{-1}

mgs = Magnesium sulfate demand of yeast culture tank, kg

mw = The ratio of maceration water per sugarcane weight, kg kg^{-1}

MF_m = Module factor for machine m

MPF_m = Material and pressure correction factor for machine m

N_m = Number of machine m

NM = Maximum limitation of nitrogen fertilizer amount, 10^3 kg ha^{-1}

OP = Operating days of cane sugar mill, d

$p(Pur)$ = Internal ratio between y_{Max} and y_n for determining $y_{n,\mathrm{Inv.}}$ at purity Pur

pdp = Potassium dihydrogen phosphate demand of yeast culture tank, kg

pH_t = Soil pH at time t, t = initial, final

Pr = Prandtl number

PM = Market price of sugarcane per stem weight, JPY (10^3 kg)$^{-1}$

PS = Subsidy paid to sugarcane farmers per stem weight, JPY (10^3 kg)$^{-1}$

$PS0$ = Standard subsidy paid to sugarcane farmers per stem weight, JPY (10^3 kg)$^{-1}$

$Pur_{j(k)}$ = Sucrose purity (in part k) in stream j, kg kg^{-1}

r = Surface contamination factor of wall for heat exchanging, m^2 K W^{-1}

R_RO= Ratio of reducing sugars to summation of reducing sugars and other brix, kg kg^{-1}

Re = Reynolds number

RS = Resale price of raw sugar per unit weight in the last second quarter, JPY (10^3 kg)$^{-1}$

rc^q = Recovery rate of material q, kg kg^{-1}

reg = Selected planting region

scr = Index representing the ease of scrapping cane tops and leaves

$soda$ = Caustic soda consumption in precipitation, kg

$soil$ = Soil type

$S(T)$ = Solubility of sucrose to water at temperature T, kg kg^{-1}

SYM = Sugarcane sugar-yield-related marker, 10^3 kg ha^{-1}

t = Time, s yr^{-1}

tl_k = Weight ratio of part k to stem, kg kg^{-1}, k = top, leaf

tr_k = Removal rate of part k in cane-cleaning process, kg kg^{-1}

T = Temperature, °C

TWC = Total working period of crystallization pans, d

U = Overall heat transfer coefficient, W m^{-2} K^{-1}

w = Mass fraction, %

wc^q = Water content in material q, kg kg^{-1}

wd = width [m]

W_m = Work of machine m, MJ
y_n = Raw sugar yield rate in nth crystallization step, kg kg^{-1}
Xc_r = Conversion of reaction r in yeast culture, kg kg^{-1}
$Xcl_{i1 \rightarrow i2}$ = Decomposition ratio of component i1 into i2 in clarification process, kg kg^{-1}
Xf_r = Conversion of reaction r in fermentation, kg kg^{-1}
$Xsf_{i1 \rightarrow i2}$ = Conversion of reaction from component i1 to i2 in selective fermentation process, kg kg^{-1}
y_n = Raw sugar yield rate in n-th crystallization step, kg kg^{-1}
y_{MAX} = Theoretical yield of raw sugar in crystallization, kg kg^{-1}
YM = Standard yield in sugar mills, kg kg^{-1}
α = Combustion efficiency, MJ MJ^{-1}
β_n = Enlargement ratio of the n+1th yeast culture tank to the n-th tank
δ_m = Heat loss rate to the air by machine m, MJ MJ^{-1}
η_m = Work efficiency of machine m, MJ MJ^{-1}
λ = Thermal conductivity, W m^{-1} K^{-1}
μ = Dynamic viscosity, Pa s
ρ = Density, 10^3 kg m^{-3}

Letters

aet = Anhydrous ethanol
AbChill = Absorption chiller
bag = Bagasse
bx = Brix
cake = Filter cake
cell = Yeast cell mass
cr(n) = nth crystallization
crr = Crop residue
CF = Clarification package
CH = Chilled water
CHW = Chilled water package
CJ = Clear juice
CL = Cooling water
CLT = Cooling tower package
CST = Cane stripper and trommel
CZ = Crystallizer
drn = Drain from multiple-effect evaporator
DD = Distillation columns and dehydration system
etoh = Ethanol
exh = Exhausted steam from multiple-effect evaporator

EFM = Ethanol fermenter
EVP(*n*) = *n*-th evaporator
fib = Fiber
Frt = Fertilization
HEX = Heat exchanger
HPSH = High-pressure steam header
i = Inside
ic = Inputted cold stream
ih = Inputted hot stream
ip = Input stream
Ir = Irrigation
JH(*n*) = *n*-th Juice Heater
leaf = Leaves of sugarcane
LPS = Low-pressure steam
LPSH = Low-pressure steam header
m = Average
mag = Magma
mas(*n*) = *n*th massecuite
mo(*n*) = *n*th molasses
ME = Multiple-effect evaporator
o = Outside
obx = Other brix
oc = Outputted cold stream
oh = Outputted hot stream
oil A = Fuel oil A
op = Output stream
org = Organic acids
pH = pH control
PCT = Power-conversion turbine
PRV = Pressure-reducing valves
red = Reducing sugars
RM = Roll mill
se(1,2) = First and second seed making in crystallization process
se(3) = Third seed making in crystallization process
si = Inner side of shell
sp = Seed preparation
stem = Cane stem of sugarcane
su(*n*) = raw sugar extracted from *n*th crystallizer

suc = Sucrose

sy = Syrup

s.yeast = Yeast for selective fermentation

Sel = Selection of planted region, cultivar and cropping type

SFM = Ethanol fermenter for SF

SYB = Invertase-defective yeast broth prepared for SF

SYC = Invertase-defective yeast culture solution prepared for SF

SYT(n) = n-th invertase-defective yeast culturing tank

top = Cane top of sugarcane

trs = Trash

YCT = Yeast culture tank

θ = Representative value

Subscripts

f = Fertilizer component, i.e., f := {N, P, K}

j = Stream

k = Part of sugarcane, i.e., k := {stem, top, leaf}

l = Cultivation, i.e., l := {Sel, pH, Frt, Ir}

m = Machine, i.e., m1 := {CST}, m2 := {RM}, m3 := {CF, ME, CZ}, m4 := {YCT, EFM, CLT1, CHW}, m5 := {DD, CLT2}

n = Crystallization step i.e., n := {1, 2, 3}

p = Process

pp = Subprocess

q = Material

r = Reaction

Superscripts

i = Component of materials, i := {suc, red, obx, water, fib, etoh, cell, org}

q = Material

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Appendix

Some tables and a figure are presented as supplementary information below.

TableA 1. List of agricultural input materials in Case Study B of Chapter 3.2.4.

Material	Process	Unit	Quantity
Manure	Soil preparation	10^3 kg ha^{-1}	20
Pesticide-Diazinon, Benfuracarb	Chemical spraying	kg ha^{-1}	60
Herbicide DCMU	Chemical spraying	kg ha^{-1}	1.25
Herbicide Metribuzin	Chemical spraying	kg ha^{-1}	1.75
Herbicide Halosulfuronmethyl	Chemical spraying	kg ha^{-1}	1.5
Herbicide Asulam	Chemical spraying	kg ha^{-1}	1
Herbicide 2,4-D	Chemical spraying	kg ha^{-1}	4
Raticide Diphacinone	Chemical spraying	kg ha^{-1}	2.5

TableA 2 Agricultural equipment capacity and fuel demand in Case Study B of Chapter 3.2.4.

		Capacity		Diesel oil demand	
Equipment	Process	Unit	Quantity	Unit	Quantity
Plow	Soil preparation (Deep plowing)	h ha^{-1}	11.1[a]	L h^{-1}	7.0[b]
Plow soiler	Soil preparation (Grinding, New planting)	h ha^{-1}	6.3[a]	L h^{-1}	7.0[c]
Rotary	Soil preparation (Tillage)	h ha^{-1}	3.9[a]	L h^{-1}	7.0[b]
Lime distributing wagon	Soil preparation (pH control)	h ha^{-1}	1.6[d]	L h^{-1}	6.0[d]
Manure spreader	Soil preparation (Manure distribution)	h ha^{-1}	8.4[a]	L h^{-1}	7.0[c]
Planter	Planting	h ha^{-1}	12.5[a]	L h^{-1}	7.0[b]
Half soiler	Soil preparation (Grinding, Ratoon)	h ha^{-1}	10.0[a]	L h^{-1}	7.0[c]
Ratoon arranger	Ratooning (Ratoon arrangement)	h ha^{-1}	14.7[a]	L h^{-1}	7.0[c]
Rotary tillage	Intertillage and earthing up	h ha^{-1}	14.7[a]	L h^{-1}	7.0[c]
Power sprayer	Chemicals spraying	h ha^{-1}	1.3[b]	L h^{-1}	7.0[b]
Harvester	Harvesting	h ha^{-1}	14.5[a]	L h^{-1}	6.6[b]
4t Truck	Transport			L km^{-1}	0.14[e]

[a]Shinzato, 2015; [b]Kagoshima Prefecture, 2014; [c]Assumption (same as Plow); [d]Macedo et al., 2004; [e]Ministry of Land, Infrastructure, Transport and Tourism, 2014.

TableA 3 Process parameters of industrial process module in Case Study B of Chapter 3.2.4.

Description	Symbol	Unit	Quantity
Pretreatment			
Electricity demand of cane stripper and trommel	$ed_{\mathrm{CST}}/\sum_k F_{\mathrm{trs}}$	kWh $(10^3\mathrm{kg})^{-1}$	12.0[a]
Fiber removal rate by roll mills	fr	kg kg^{-1}	1.00[b]
Leaching rate of brix in trash into cane juice by roll mills	ebt	kg kg^{-1}	0.22[b]
Bagasse water content	wc^{bag}	kg kg^{-1}	0.45[c]
HPS demand of roll mills	$hd_{\mathrm{RM}}/F^{\mathrm{bag}}$	MJ $(10^3\mathrm{kg})^{-1}$	207[d]
Work efficiency of roll mills	η_{RM}	MJ-work MJ^{-1}	0.10[d]
Cylinder oil* consumption of roll mills	$\mathrm{cyl}/\sum_k F_{\mathrm{I1}(k)}$	L $(10^3\mathrm{kg})^{-1}$	0.0273[d]
Clarification			
Slaked lime addition rate to cane juice	la	kg $(10^3\mathrm{kg})^{-1}$	0.85[e]
Sucrose removal rate by clarification package	fcr^{suc}	kg kg^{-1}	0.015[d]
Reducing sugar removal rate by clarification package	fcr^{red}	kg kg^{-1}	0.015[d]
Other brix removal rate by clarification package	fcr^{obx}	kg kg^{-1}	0.40[e]
Fiber removal rate by clarification package	fcr^{fib}	kg kg^{-1}	1.00[b]
Filter cake water content	wc^{cake}	kg kg^{-1}	0.62[d]
LPS demand of clarification package	$ld_{\mathrm{CF}}/F_{\mathrm{I3}}$	MJ $(10^3\mathrm{kg})^{-1}$	109[d]
Cleaning agent* addition in precipitation	$clag/F_{\mathrm{I3}}$	kg $(10^3\mathrm{kg})^{-1}$	0.0433[d]
Caustic soda* addition in precipitation	$soda/F_{\mathrm{I3}}$	kg $(10^3\mathrm{kg})^{-1}$	0.0389[d]
Evaporation			
Target brix concentration of syrup in multiple-effect evaporators	bxo_{sy}	kg kg^{-1}	0.60[e]
LPS demand of multiple-effect evaporator	$ld_{\mathrm{ME}}/(F_{\mathrm{exh}} + F_{\mathrm{drn}})$	MJ $(10^3\mathrm{kg})^{-1}$	570[d]
Work efficiency of multiple-effect evaporator	η_{ME}	MJ-work MJ^{-1}	0.32[d]
Ratio of emitted energy as exhausted steam to given energy	$\delta_{\mathrm{ME-exh}}$	MJ MJ^{-1}	0.18[d]
Ratio of emitted energy as drain to given energy	$\delta_{\mathrm{ME-drn}}$	MJ MJ^{-1}	0.50[d]

TableA 3 Process parameters of industrial process module in Case Study B of Chapter 3.2.4. (*Continued*)

Description	Symbol	Unit	Quantity
Sugar production			
Target brix concentration of 1st molasses	$bxo_{\mathrm{mo}(1)}$	kg kg^{-1}	0.80[e]
Target brix concentration of 2nd molasses	$bxo_{\mathrm{mo}(2)}$	kg kg^{-1}	0.70[e]
Sucrose purity of 1st raw sugar	$pur_{\mathrm{su}(1)}$	kg kg^{-1}	0.97[e]
Sucrose purity of 2nd raw sugar	$pur_{\mathrm{su}(2)}$	kg kg^{-1}	0.97[e]
Sucrose purity of 3rd raw sugar	$pur_{\mathrm{su}(3)}$	kg kg^{-1}	0.86[e]
Distribution ratio from syrup to seed preparation	$d_{\mathrm{sy,sp}}$	kg kg^{-1}	0.22[d]
Distribution ratio from syrup to 1st crystallizer	$d_{\mathrm{sy,cr}(1)}$	kg kg^{-1}	0.65[d]
Distribution ratio from syrup to 2nd crystallizer	$d_{\mathrm{sy,cr}(2)}$	kg kg^{-1}	0.04[d]
Distribution ratio from syrup to 3rd seed	$d_{\mathrm{sy,se}(3)}$	kg kg^{-1}	0.06[d]
Distribution ratio from syrup to magma	$d_{\mathrm{sy,mag}}$	kg kg^{-1}	0.03[d]
Distribution ratio from 1st and 2nd seed to 1st crystallizer	$d_{\mathrm{se}(1,2),\mathrm{cr}(1)}$	kg kg^{-1}	0.73[d]
Distribution ratio from 1st and 2nd seed to 2nd crystallizer	$d_{\mathrm{se}(1,2),\mathrm{cr}(2)}$	kg kg^{-1}	0.27[d]
Distribution ratio from 1st molasses to 1st crystallizer	$d_{\mathrm{mo}(1),\mathrm{cr}(1)}$	kg kg^{-1}	0.23[d]
Distribution ratio from 1st molasses to 2nd crystallizer	$d_{\mathrm{mo}(1),\mathrm{cr}(2)}$	kg kg^{-1}	0.51[d]
Distribution ratio from 1st molasses to 3rd seed	$d_{\mathrm{mo}(1),\mathrm{se}(3)}$	kg kg^{-1}	0.26[d]
Distribution ratio from 2nd molasses to 3rd crystallizer	$d_{\mathrm{mo}(2),\mathrm{cr}(3)}$	kg kg^{-1}	1.00[d]
Distribution ratio from 2nd molasses to 3rd seed	$d_{\mathrm{mo}(2),\mathrm{se}(3)}$	kg kg^{-1}	0[d]
Raw sugar recovery rate in centrifuge	rc^{su}	kg kg^{-1}	0.99[b]
Molasses recovery rate in centrifuge	rc^{mo}	kg kg^{-1}	0.99[b]
Adhesive molasses rate with 3rd sugar to the molasses before centrifuge	mc	kg kg^{-1}	0.10[b]
LPS demand of crystallizers	$ld_{\mathrm{CZ}}/\sum_{n} F_{\mathrm{su}(n)}$	MJ (10^{3}kg)$^{-1}$	4598[d]
Work efficiency of crystallizers	η_{CZ}	MJ-work MJ^{-1}	0.76[d]

TableA 3 Process parameters of industrial process module in Case Study B of Chapter 3.2.4. (*Continued*)

Description	Symbol	Unit	Quantity
Sugar production			
Electricity demand of equipment from milling to crystallization process	$\sum_{m \in m2,m3} ed_m / \sum_k F_{I1(k)}$	kWh $(10^3 kg)^{-1}$	23.9[d]
Ethanol production			
Target sucrose and reducing sugar concentration of molasses		kg kg^{-1}	0.20[f]
Distribution ratio of diluted molasses to yeast culture tank		kg kg^{-1}	0.10[g]
Conversions of yeast culture:			
Sucrose to reducing sugars	$Xc_{suc \to red}$	kg kg^{-1}	1.00[g]
Reducing sugars to ethanol	$Xc_{red \to etoh}$	kg kg^{-1}	0.90[g]
Reducing sugars to yeast	$Xc_{red \to yeast}$	kg kg^{-1}	0.04[g]
Reducing sugars to organic acids	$Xc_{red \to org}$	kg kg^{-1}	0.01[g]
Electricity demand of yeast culture tank	ed_{YCT}/F_{I5-1}	kWh $(10^3 kg)^{-1}$	2.90[g]
CH demand of yeast culture tank	chd_{YCT}/F_{I5-1}	MJ-CH $(10^3 kg)^{-1}$	457[g]
Ammonium sulfate demand of yeast culture tank*	$ams/\left(F_{I5-1}^{suc} + F_{I5-1}^{red}\right)$	kg $(10^3 kg)^{-1}$	177[h]
Potassium dihydrogen phosphate demand of yeast culture tank*	$pdp/\left(F_{I5-1}^{suc} + F_{I5-1}^{red}\right)$	kg $(10^3 kg)^{-1}$	38.1[h]
Magnesium sulfate demand of yeast culture tank*	$mgs/\left(F_{I5-1}^{suc} + F_{I5-1}^{red}\right)$	kg $(10^3 kg)^{-1}$	8.20[h]
Conversions of ethanol fermentation:			
Sucrose to reducing sugars	$Xf_{suc \to red}$	kg kg^{-1}	1.00[g]
Reducing sugars to ethanol	$Xf_{red \to etoh}$	kg kg^{-1}	0.95[g]
Reducing sugars to cell mass	$Xf_{red \to cell}$	kg kg^{-1}	0.02[g]
Reducing sugars to organic acids	$Xf_{red \to org}$	kg kg^{-1}	0.03[g]
Electricity demand of fermenter	$ed_{EFM}/(F_{I5-2} + F_{I5-3})$	kWh $(10^3 kg)^{-1}$	3.15[g]
CL demand of fermenter	$cld_{EFM}/(F_{I5-2} + F_{I5-3})$	MJ-CL $(10^3 kg)^{-1}$	89.1[g]
Target concentration of ethanol		kg kg^{-1}	0.995[g]
Electricity demand of distillation and dehydration package	ed_{DD}/F_{I6}	kWh $(10^3 kg)^{-1}$	1.70[g]
LPS demand of distillation and dehydration package	ld_{DD}/F_{I6}	MJ $(10^3 kg)^{-1}$	362[g]
CL demand of distillation and dehydration package	cld_{DD}/F_{I6}	MJ-CL $(10^3 kg)^{-1}$	291[g]

TableA 3 Process parameters of industrial process module in Case Study B of Chapter 3.2.4. (*Continued*)

Description	Symbol	Unit	Quantity
Ethanol production			
Coefficient of performance (COP) of cooling tower package	ed_{CLT}/cld	kWh kWh^{-1}	111[g]
COP of chilled water package	ed_{CHW}/chd	kWh kWh^{-1}	6.28[g]
Energy cogeneration			
LHV of fuel oil A	$H_{\mathrm{oil-A}}$	MJ L^{-1}	37.2
Latent heat of steam	h_{steam}	MJ kg^{-1}	2.26
Boiler efficiency	α	MJ MJ^{-1}	0.96[d]
Heat loss rate of HPSH	δ_{HPSH}	MJ MJ^{-1}	0.05[d]
Heat loss rate of LPSH	δ_{LPSH}	MJ MJ^{-1}	0.04[d]
Heat loss rate of PRV	δ_{PRV}	MJ MJ^{-1}	0.12[d]
Work efficiency of PCT	η_{PCT}	MJ MJ^{-1}	0.10[d]
Heat loss rate of PCT	δ_{PCT}	MJ MJ^{-1}	0.01[d]
Others			
LHV of ethanol	H_{aet}	MJ L^{-1}	21.2
Density of anhydrous ethanol	ρ_{aet}	kg L^{-1}	0.789
Boiler compound* consumption through the whole processes	$bcmp$	kg (10^3kg)$^{-1}$	0.0458[d]

*Not a component in the model but considered in the economic evaluation.

[a] Rein et al., 2007; [b] Assumption; [c] Hugot, 1960; [d] Kikuchi et al., 2015 (Actual data of sugar mills); [e] Yamane, 1967.
[f] Basso et al., 2008; [g] Humbird et al., 2011; [h] Yanagida et al., 2010

TableA 4. Unit prices of items used Case Study B of Chapter 3.2.4.

Item	Unit	Unit price
Farmer		
Property expenses	10^5 JPY ha^{-1}	6.89[a]
Labor expenses	10^5 JPY ha^{-1}	8.12[a]
Product		
Raw sugar	JPY kg^{-1}	87.2[b]
Ethanol	JPY L^{-1}	67.2[c*]
Bagasse, Trash	JPY MJ^{-1}	1.53[c*]
Gasoline	JPY L^{-1}	104[c]
Fertilizer-N (in by-product)	JPY (kg-N)$^{-1}$	288[d*]
Fertilizer-P (in by-product)	JPY (kg-P)$^{-1}$	1,035[d*]
Fertilizer-K (in by-product)	JPY (kg-K)$^{-1}$	265[d*]
Utility		
Slaked lime	JPY kg^{-1}	28[d]
Cylinder oil	JPY L^{-1}	450[d]
Chitosan (Cleaning agent)	JPY kg^{-1}	3,000[d]
Caustic soda	JPY kg^{-1}	72[d]
Sodium carbonate (Boiler compound)	JPY kg^{-1}	55[d]
Ammonium sulfate	JPY kg^{-1}	61[d]
Potassium dihydrogen phosphate	JPY kg^{-1}	570[d]
Magnesium sulfate	JPY kg^{-1}	65[d]
Water	JPY (10^3 kg)$^{-1}$	35[e]
Fuel oil A	JPY L^{-1}	57[d]
Labor		
Personnel expenses	10^4 JPY person^{-1} day^{-1}	1.22[f]
Transport		
4t truck*	JPY km^{-1}	163[g]

*4t truck can carry 4×10^3 kg of sugarcane or by-products at maximum per round trip.

[a] Average of the ten years from 2005 to 2014. Calculated from the statistics of Ministry of Agriculture, Forestry and Fisheries of Land, Japan; [b] ALIC; [c] Agency for Natural Resources and Energy; [d] The Chemical Daily, 2015; [e] Okinawa Prefectural Enterprise Bureau; [f] Estimated from statistical data. See the main text; [g] Ministry of Land, Infrastructure, Transport and Tourism, 2008.

TableA 5. Inventory data for GHG emissions in the manufacturing and transporting of items

Item	Unit	Quantity
Manure	kg-CO_2eq kg-dry^{-1}	0.429[a]
Calcium carbonate	kg-CO_2eq (10^3 kg)$^{-1}$	3.55[a]
Slaked lime	kg-CO_2eq kg^{-1}	0.908[a]
Herbicide	kg-CO_2eq kg^{-1}	14.2[b]
Pesticide	kg-CO_2eq kg^{-1}	14.1[b]
Raticide	kg-CO_2eq kg^{-1}	14.1[b]
Fertilizer N	kg-CO_2eq kg-N^{-1}	1.37[b]
Fertilizer P_2O_5	kg-CO_2eq kg-$P_2O_5$$^{-1}$	0.476[b]
Fertilizer K_2O	kg-CO_2eq kg-$K_2O$$^{-1}$	0.508[a]
Water	kg-CO_2eq m^{-3}	0.119[a]
Diesel oil	kg-CO_2eq L^{-1}	0.184[c]
Fuel oil A	kg-CO_2eq L^{-1}	0.243[c]

[a] JLCA, 2013, Ecoinvent Database v. 2.2. and MiLCA, 2012; [b] Kobayashi et al., 2006;
[c] Petroleum Energy Center, 2000.

TableA 6. Inventory data for GHG emissions in the consumption or decomposition of items

Item	Unit	Quantity
Calcium carbonate	kg-CO_2 kg^{-1}	0.44[a]
Diesel oil	kg-CO_2 L^{-1}	2.64[b]
Fuel oil A	kg-CO_2 L^{-1}	2.70[a]
Soil (Deep plowing)	kg-N_2O-N ha^{-1}	8.00[a]
Manure	kg-N_2O-N kg-N^{-1}	0.0062[a]
Nitrogen fertilizer	kg-N_2O-N kg-N^{-1}	0.0062[a]
Residue (Decomposition)	kg-N_2O-N kg-N^{-1}	0.0125[a]
Residue (Combustion)	g-N_2O kg dry^{-1}	0.07[a]
	g-CH_4 kg dry^{-1}	2.70[a]

[a] Ministry of the environment Japan, 2015; [b] Petroleum Energy Center, 2000.

TableA 7. Carbon content of each component

Component	Carbon content	
	Unit	Value
Sucrose	kg kg^{-1}	0.421
Reducing sugars	kg kg^{-1}	0.400
Other brix	kg kg^{-1}	0
Fiber	kg kg^{-1}	0.500
Ethanol	kg kg^{-1}	0.522
Cell mass	kg kg^{-1}	0.400
Organic acids	kg kg^{-1}	0.400

TableA 8. Carbon content of fiber component and fiber composition

Fiber component	Carbon content		Fiber composition	
	Unit	Value	Unit	Value
Cellulose	kg kg^{-1}	0.445	%	50.3
Hemicellulose	kg kg^{-1}	0.455	%	23.8
Lignin	kg kg^{-1}	0.648	%	26.0

TableA 9. Nitrogen, phosphate and potassium content of by-products

By-products	Unit	N	P	K
Ash[a]	kg (10^3kg-ash)$^{-1}$	0	6.4	42.3
Filter cake[b]	kg (10^3kg-cake*)$^{-1}$	16.8	11.3	3.1
Vinasse[c]	kg (m^3-vinasse)$^{-1}$	0.28	0.10	1.17

*Dry basis

[a] Rein P, 2007; [b] Dee BM et al., 2002; [c] Lisboa CC et al., 2011.

Table A10. Input Material for the Culturing Tank

Material	Process	Unit	Quantity
Phosphoric acid (98.5% in water)	Culturing (s.yeast)	kg (kL-SYC)$^{-1}$	0.6
Ammonia solution (10% in water)	Culturing (s.yeast)	kg (kL-SYC)$^{-1}$	2.7
Antifoam agent	Culturing (s.yeast)	kg (kL-SYC)$^{-1}$	1.0
Invertase	Culturing (s.yeast)	10^{-6} kg (kg-SYC)$^{-1}$	50.0
Molasses (Purchased, Brix = 80%)*	Culturing (s.yeast)		
Sulfuric acid solution (Normality 8.4N)	Sterilization	10^{-3} L kg^{-1}	15.0
Caustic soda solution (Normality 6.3N)	Sterilization	10^{-3} L kg^{-1}	20.0

*Molasses are added until s. yeast reaches the required amount.

Table A11 Distribution Ratio of Syrup, First and Second Molasses in the case study of Chapter 3.3.3.

Description	Symbol	Unit	Quantity
Distribution ratio from syrup to 2nd crystallization pan	$d_{\mathrm{sy,cr(2)}}$	kg kg^{-1}	0
Distribution ratio from syrup to 3rd seed	$d_{\mathrm{sy,se(3)}}$	kg kg^{-1}	0
Distribution ratio from 1st molasses to 1st crystallization pan	$d_{\mathrm{mo(1),cr(1)}}$	kg kg^{-1}	0
Distribution ratio from 1st molasses to 3rd seed	$d_{\mathrm{mo(1),se(3)}}$	kg kg^{-1}	0.132
Distribution ratio from 2nd molasses to 3rd crystallization pan	$d_{\mathrm{mo(1),se(3)}}$	kg kg^{-1}	0.895

Table A12 Process Parameters of Clarification and Selective Fermentation Process in the case study of Chapter 3.3.3.

Description	Symbol	Unit	Quantity
Decomposition ratio of sucrose into RS in clarification process		kg (10^{3}kg)$^{-1}$	8.5
Temperature of cane juice after the 1st juice heater	$T_{\mathrm{JH(1)}}$	°C	65
Temperature of cane juice after the 2nd juice heater	$T_{\mathrm{JH(2)}}$	°C	103
Number of 1st yeast culture tank	N_{SYT1}	-	1
Number of 2nd yeast culture tank	N_{SYT2}	-	2
Number of 3rd yeast culture tank	N_{SYT3}	-	2
Scale ratio of culture tank to the last	β	-	100
Ratio of headspace volume to working volume in yeast culture tank		-	0.50
Initial brix concentration of yeast culture solution		-	0.20
Initial density of yeast (wet) culture solution		kg L^{-1}	1.08
Final density of yeast (wet) culture solution		kg L^{-1}	1.04
Final concentration of yeast (wet) in 1st yeast culture solution		kg kg^{-1}	0.06
Final concentration of yeast (wet) in 2nd yeast culture solution		kg kg^{-1}	0.06
Final concentration of yeast (wet) in 3rd yeast culture solution		kg kg^{-1}	0.03
Number of ethanol fermenter for SF	N_{SFT}	-	3
Concentration of yeast in fermenter for SF	$CY_{\mathrm{SFM}}^{\mathrm{targ}}$	kg L^{-1}	0.06
Concentration of yeast in prepared yeast broth	$CY_{\mathrm{SYB}}^{\mathrm{targ}}$	kg L^{-1}	0.20
Density of prepared yeast broth	ρ_{SYE}	kg L^{-1}	1.08
Density of prepared yeast culture solution	ρ_{SYC}	kg L^{-1}	1.04
Initial concentration of yeast in SF	CY_{SFL}	kg L^{-1}	0.06
Time of SF in one cycle	CT	h	3
Temperature of SF	T_{SF}	°C	35

Table A12 Process Parameters of Clarification and Selective Fermentation Process in the case study of Chapter 3.3.3. (*Continued*)

Description	Symbol	Unit	Quantity
Durability of yeast	DY	d	30
Heat of reaction per RS weight in SF		MJ $(10^3\text{kg})^{-1}$	655
Ratio of dry yeast to wet yeast by weight		kg kg^{-1}	0.22
Conversion ratio from sucrose to ethanol	$Xsf_{\text{suc}\rightarrow\text{red}}$	kg kg^{-1}	0
Conversion ratio from RS to ethanol	$Xsf_{\text{red}\rightarrow\text{etoh}}$	kg kg^{-1}	0.85
Conversion ratio from RS to s. yeast	$Xsf_{\text{red}\rightarrow\text{cell}}$	kg kg^{-1}	0.045
Conversion ratio from reducing sugar to organic material other than ethanol	$Xsf_{\text{red}\rightarrow\text{org}}$	kg kg^{-1}	0.105
Electricity demand of culture tank		kWh $(\text{t-yeast})^{-1}$	2.46
Electricity demand of pump		kWh $(\text{t-juice})^{-1}$	0.15
Electricity demand of ethanol fermenter		kWh $(\text{kL-liquid})^{-1}$	0.0219
Coefficient of performance (COP) of cooling tower		kW-elec $(\text{kW-cooling})^{-1}$	70.2
Coefficient of performance (COP) of absorption chiller		MJ-work $(\text{MJ-LPS})^{-1}$	1.36
Coefficient of performance (COP) of electric chiller		MJ-work $(\text{MJ-elec})^{-1}$	3.72

Table A 13 Basic settings of heat exchangers in the case study of Chapter 3.3.3.

Parameter	Unit	Value
Shell and tube type		
d_w	m	0.002
D_o/D_i	-	1.09
D_o/D_m	-	1.19
Tube length, Lt	m	6 (HEX1, 3, 4) or 15 (HEX2)
Spiral type		
d_w	m	0.002
D_o/D_i	-	1.09
D_o/D_m	-	1.19
Width of plates, B	m	0.6
Stream length, Ls	m	12

Table A14. Process Parameters of the Crystallization Process in the case study of Chapter 3.3.3.

Operation	Required time		Charge-in quantity		Water addition	
	Unit	Value	Unit	Value	Unit	Value
Graining	h $batch^{-1}$	10.0	t-feed $batch^{-1}$	12	t-water t^{-1}	0.04
1st crystallization	h $batch^{-1}$	6.5	t-feed $batch^{-1}$	85	t-water t^{-1}	0.03
2nd crystallization	h $batch^{-1}$	7.3	t-feed $batch^{-1}$	38	t-water t^{-1}	0.51
3rd crystallization	h $batch^{-1}$	8.2	t-feed $batch^{-1}$	28	t-water t^{-1}	0.38
Seed boiling	h $batch^{-1}$	6.2	t-feed $batch^{-1}$	89	t-water t^{-1}	0.51

Table A15. Design Parameters Related to SF.

Equipment	a [10^4]	b [-]	c [10^4]
1st yeast culturing tank	59	1	9877
Other tank (Summation of the following two items)			
Base	2.9	1	902.7
Vessel	1091	0.513	0

The base and the vessel of the other tank are assumed to equal those of the ring tank and the corn-roof tank listed in "Cost Handbook for Chemical Equipment (Saito, 2000)," respectively.

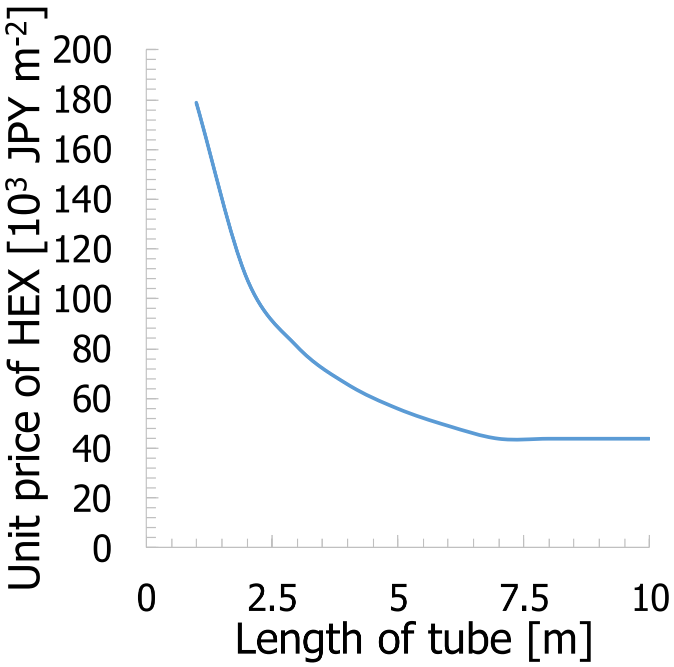

Figure A 1 Initial cost of double-pipe heat exchanger including main unit (Obana, 2011).

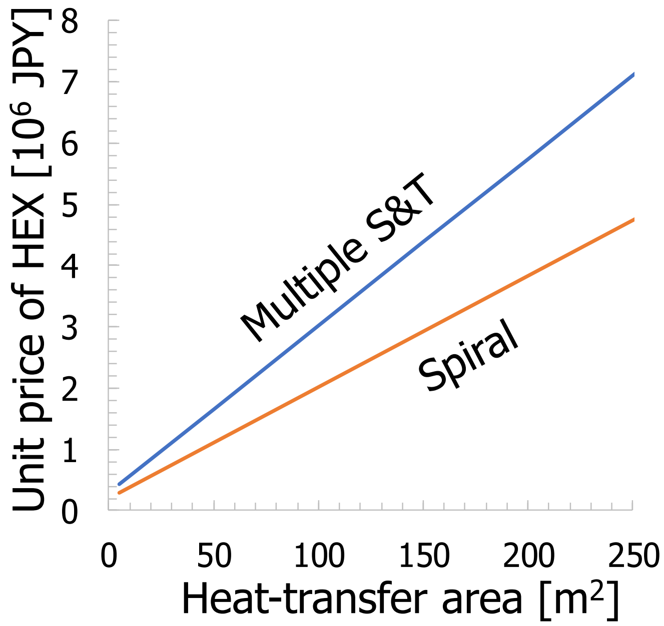

Figure A 2 Initial cost of other heat exchangers including main units (Obana, 2011).

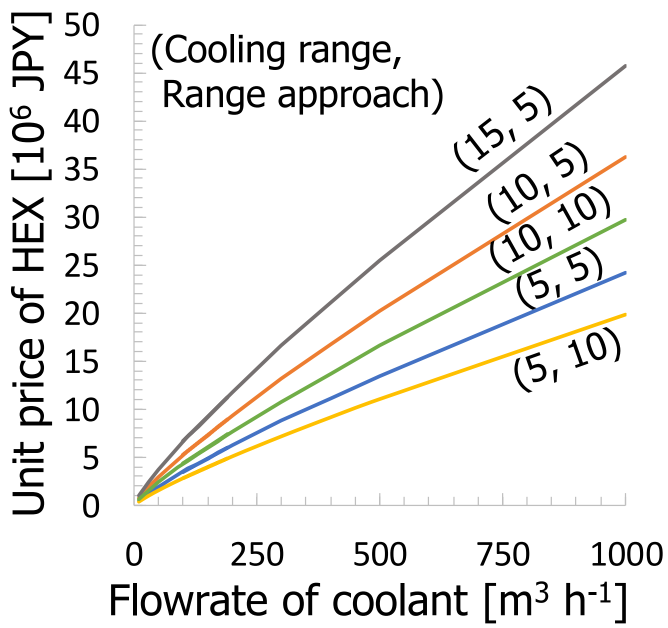

Figure A 3 Initial cost of cooling tower including main unit, fan, electric motor, reducer, emplacement construction, painting and test operation (Satio, 2000).