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SPECIAL FEATURE: ORIGINAL ARTICLE

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A probabilistic economic model and sensitivity analysis of fuel-oil production from plastic waste

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Abstract

Pyrolysis of plastic waste has been studied for many years, but there are only a few commercial plants in the world. A probabilistic economic model was applied to a fuel-production business from plastic waste. Many parameters governing the business balance such as collection amount of plastic waste, oil yield and gate fee often fluctuate during a business period. The model parameters were determined from reports or interviews and assumed to fluctuate along the normal distribution, unlike fixed values of several sets of parameters in conventional case studies of economic feasibility. The probability of business success, *Ps*, was defined as the probability of a positive business balance. The total balance was calculated using 17 parameters, which were assumed to fluctuate randomly along the normal distribution for a business period of 20 years. The probability of success was obtained by the Monte Carlo method with 3000 calculations using the fluctuating parameters. Sensitivity analysis was also conducted to measure the effect of each typical parameter on *Ps*. Among the parameters examined, gate fee is the most influential. The probability of success increased by 69% with a gate fee of 1.1-times the average and decreased by 28% with a gate fee of 0.9-times the average.

Keywords Economic model · Probabilistic approach · Sensitivity analysis · Plastic waste · Pyrolysis

Introduction

Since the 1970s, conversion of plastic waste into chemical feedstock and fuel through pyrolysis has been studied in both academics and practical engineering fields [1–5]. Pyrolysis technology had been demonstrated to produce a fuel or feedstock in a petrochemical process typically in Germany and Japan [6–9]. In Japan, more than 30 commercial pyrolysis plants had been installed, and the most plants already stopped their operation [10]. In particular, three large-sized pyrolysis plants (20 to 40 tons/day) were commercially operated for oil production under the containers and packaging law for plastic waste from households around the year 2000. These plants stopped operating after about 10 years. A few pyrolysis plants for industrial plastic waste (typically two series with a capacity of three tons/day) are still operating in the country. This suggests that technical challenges in this business are not serious, but issues nonetheless exist. Thus, economic feasibility of waste business should be conducted to identify and prevent business risks.

Waste business, which includes conversion of plastic waste into oil, often faces various obstacles due to economic and social conditions, such as workers' wages, gate fee of a competitive method in other waste industries, the generation amount of the target component for resource utilization, waste composition, and accuracy of separate disposal at the waste source. In the actual world of business, many parameters relating to the economic balance fluctuate during the business period. For example, annual collection of plastic waste, composition of plastic waste, and the amount

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of fuel-oil produced will change by operation and by year. These fluctuations govern the business profits and expenses, and often interrupt the business activities due to the poor business balance. One such business is fuel production from plastics through pyrolysis.

Economic feasibility studies on fuel-oil production business from municipal waste [11] and plastic waste [12] were conducted by the conventional deterministic approach. Feasibility studies usually use several sets of fixed values as calculation parameters of business balance in the entire business period. Business profits depend on the parameters such as waste collection amount, thermoplastic contents that can be converted into fuel-oil and sales price of products. In fact, some values such as feed composition, product yield, collection amounts and gate fee often fluctuate during a business period, so only parameters that vary within a workable range should be considered to estimate economic balance. Although feasibility studies would be conducted in the business of plastic waste conversion, various obstacles led the most companies to withdraw from the business. It is important to perform risk analysis, which considers uncertainty of business conditions in an engineering project [13–15]. There are few reports on business risks in fuel-oil production business from plastic waste.

The net present values (NPV) and the return on investment (ROI) were calculated and sensitivity analysis was conducted by choosing two parameters that would cause the business risk in fuel production business from plastic waste [12]. NPV was calculated by 36 combinations of six values as the unit production cost and six values as the unit sales price of fuel under the other business parameters with constant values. The sensitivity analysis changing two parameters showed that three cases out of 36 combinations gave the negative NPV.

For describing implicit risks associated with business conditions, probabilistic economic analysis is used for assessing economic feasibility of various types of businesses and projects, using distributed parameters under dynamic business environments rather than several sets of fixed parameters. This approach was used in various studies such as an agriculture project [16], process selection of biofuel production [17, 18], estimation of sales price of biofuel [19], estimation of NPV of biofuel production [20, 21] and estimation of NPV and the probability of success of a mineral recovery business [22]. These papers mainly focused on estimation of NPV with a probable distribution rather than seeking the risk factor influencing to the business profit. It is crucial for a business planner or investor to evaluate the economic feasibility of a business under various conditions and the influence of different parameters on the business balance. The probabilistic approach employed in this study fills this research gap and enables us to assess economic feasibility and conduct sensitivity analysis, which indicates the degree of influence of each parameter on the business balance.

In this paper, we applied a probabilistic model to a fuel production business from plastic waste to evaluate its economics using fluctuating parameters, which govern the economic balance during a business period. As the model parameters, operation data and the business conditions of the commercial plant of Sapporo, Japan were used. Sensitivity analyses of typical parameters were also conducted to identify the parameter that most affects the total balance.

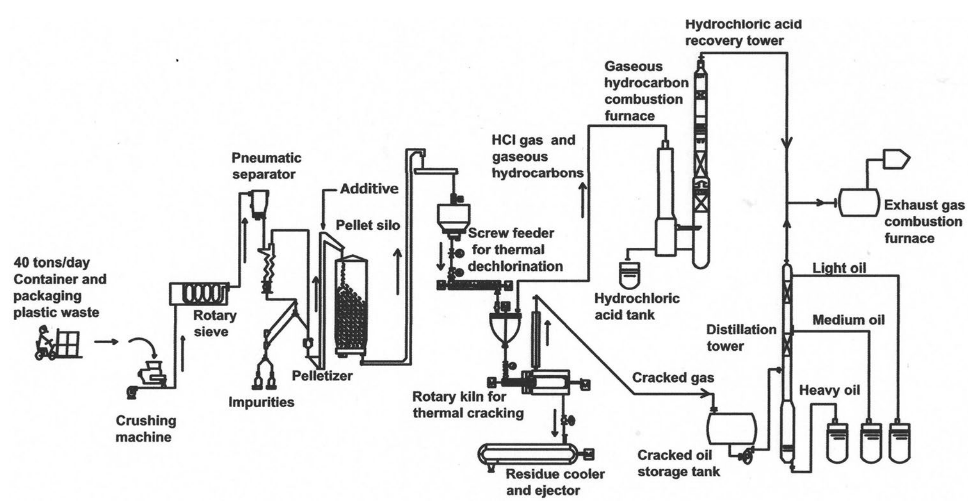

Fig. 1 Flow diagram of the fuel-production facility operated by Sapporo Plastic Recycle Co., Ltd

Methodology

Process outline for economic assessment

Figure 1 shows a schematic diagram of a pyrolysis plant for converting plastic waste from households into fuel-oil. This plant was commercially operated at 40-metric tons/day treatment scale in 2000 – 2010 by Sapporo Plastic Recycle Co., Ltd. One of the authors, H. Ibe, was engaged in designing the plant and establishing the stable operation of it. Plastic wastes were collected under the containers and packaging law in Japan. A municipal government collects plastic wastes of containers and packaging regularly. Separate disposal of plastic waste was conducted at households and contaminations of plastic waste were roughly removed from the plastic waste in a sorting facility of a municipal government.

ESM_Table 1 shows the specifications of the major equipment in the fuel-oil production plant. Fue-oil production process is explained as follows: Bales of plastic wastes in the size of 1 × 1 × 1.3 m and weighing 130 – 200 kg were transported from municipalities to a pretreatment facility of the plant. They were shredded, dried, sorted, and pelletized to about 6 mm diameter × 20 mm length pellets which were stored in pellet silos after mixing with calcium hydroxide. The pellets were fed to an extruder for dechlorination at 300–330 °C. The molten plastics were fed into a rotary kiln for pyrolysis after degassing in a molten polymer vessel. Mixed flue gas of hydrogen chloride and gaseous hydrocarbons from the dechlorination process was incinerated to burn the hydrocarbons. The hydrocarbon-free exhaust gas from the incinerator was absorbed with water in a hydrochloric acid recovery tower to obtain hydrochloric acid. The incinerator and its operating conditions were designed and operated to prevent air pollution. The molten waste plastics after dechlorination was fed into an external heating rotary kiln for pyrolysis at 400–450 °C. Vaporized hydrocarbons discharged from the rotary kiln was condensed, stored in a storage tank and distilled into three fractions; light oil, medium oil and heavy oil. Off-gas that is the non-condensable portion was incinerated. Solid residue generated in the rotary kiln, which was dry and fine particle size powder, was periodically discharged from the bottom of the rotary kiln and transferred to a residue tank through a cooling jacket chain-conveyer.

The operation results of the plant are summarized in ESM_Table 2. It shows that many observations, such as product yield, fluctuated during the operation period. Fluctuations were also observed in electricity consumption and heat consumption in dechlorination and pyrolysis, depending on the amount and quality of plastic waste being fed to the system. Some operation results, including analytical results of wastewater and flue gas, were reported in a previous study [8, 9].

Table 1 lists the parameters and baseline conditions for assessing the economic feasibility of a fuel-oil production business from plastic waste. Figures 2 and 3 present graphical explanations of the parameters. The fuel-oil production process of a model plant of scale 30 tons/year is assumed to follow the same process design as the commercial plant at Sapporo, shown in Fig. 1. The typical components of the collected plastic wastes are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyvinylidene dichloride (PVDC), polyethylene terephthalate (PET), laminates of multiple plastic film, moisture, and impurities of non-plastic materials.

PE, PP, and PS are the typical plastics in household waste that yield liquid and gaseous hydrocarbons. As shown in Fig. 3, oil, gaseous hydrocarbons and carbonaceous solid residue were defined as the pyrolysis products for sale or fuel that were used in the plant. PVC, PVDC and PET yield only a little liquid hydrocarbon at pyrolysis. Plastic waste collected from households also contain non-plastic substances, treated as impurities. These are metals, including aluminum foil and laminate, ceramics, paper, and moisture. Thus, PE, PP, and PS are the main target plastics to be collected for liquid-fuel production.

As shown in Fig. 3, the amount of plastic waste fed into a rotary kiln is defined as *PF*, which is equal to $P1(1—P5/100)$, where $P1$ is collection amounts of plastic waste in a year, and $P5$ is impurity content of the plastic waste in weight percent. *PF* is the amount of a mixed plastics with moisture feeding to the dechlorination process.

The major pyrolysis product is liquid hydrocarbon, and the by-products are gaseous hydrocarbons called off-gas and a carbonaceous solid residue called as a char. Liquid product is usually used as fuel-oil for diesel-oil or heavy-oil substitutes. An oil refinery once accepted a part of the product from Sapporo plant, Japan, to mix it with crude oil feeding to a topper for commercial operation. The oil product was also used as fuel for burners equipped with pyrolysis reactors and for power generators in the facility. Liquid hydrocarbons have a wide range of boiling points. Considering users' demand, they are collected as a whole oil, or three fractions of light oil, medium oil, and heavy oil, corresponding to gasoline, diesel oil, and heavy oil, respectively. Gaseous hydrocarbons are also obtained and can be used inside the facility or sold to the users near the facility as fuel.

Calculation procedure

The study examined the economic feasibility of fuel-oil production from plastic waste. Moreover, sensitivity analysis was introduced into the economic feasibility analysis. The economic balance was calculated according to the data

Table 1 Parameters and the baseline conditions of fuel-oil production in this study

Parameters, symbol	Baseline value μ, unit	Standard deviation σ	Remarks
Operation period, *n*	20 year	–	Example of a business period of fuel-oil production from plastics
Amount of plastic waste, *P1*	9900 tons/year	990	Collected amount of segregated plastic waste transported from a municipal government
Treatment capacity, *P2*	9900 tons/year	990	Total treatment capacity of three lines of a 10-ton/day capacity system, $P2 = 10$ (ton/day line) × 3 (lines) × 330 (days/year)
Gate fee, *P3*	434 USD/ton	43.4	Mean bid price of feedstock recycling of plastic wastes under the containers & packaging law
Product yield, *P4*	58 wt%	5.8	Percent yield of hydrocarbon oil and gas for sale to *P1* excluding fuel amounts consumed for a pyrolysis system in the facility
Impurity content, *P5*	2 wt%	0.2	Weight percentage of non-plastic impurities in waste to *P1*
Unit sales price of oil and gas, *P6*	567 USD/ton	56.7	Mean unit price of product oil and gas for sale, assuming 30% discount to the average heavy-oil price in Japan
Unit sales price of solid fuel, *P7*	100 USD/ton	10.0	Unit sales price of solid fuel
Target plastics content, *PT*	78 wt%	7.8	Weight percentage of PE, PP, and PS to the waste plastics collected from households
Feeding amount, *PF*	9702 tons/year	970.2	Input amount of wastes to a pyrolysis plant after pretreatment, $PF = P1 \times (1 - P5/100)$
Yield of solid residue, *PR*	16 wt%	1.6	Weight percentage of solid residue to *PF* given by pyrolysis, assuming that it is used for solid fuel for sale
Unit pretreatment cost, *E1*	100 USD/ton	10.0	Operation cost of pretreatment per waste plastics amount collected, typically expense of calcium hydroxide and electricity fee. Labor cost for handling a waste is included
Unit pyrolysis cost, *E2*	400 USD/ton	40.0	Operation cost per plastic waste amount fed to a pyrolysis process, including the expenses of electricity and water and labor cost for operating pyrolysis, distillation and for handling solid residue and product oil
Annual management cost, *Em*	1,120,000 USD/year	112,000	Fixed expenses for facility management, including labor cost of employees (manager and other office staffs), tax, insurance and maintenance cost of equipment
Core system cost, *Ec*	9,300,000 USD	930,000	Three lines of a pyrolysis plant of 10-tons/day capacity, including three rotary kilns and incidental equipment
Pretreatment system cost, *Ep*	1,120,000 USD	112,000	Equipment cost for pretreatment of plastic wastes
Distillation system cost, *Ed*	7,000,000 USD	700,000	Equipment cost for distillation and storage of pyrolysis oil and off-gas combustion
Unit waste treatment cost, *Ew*	210 USD/ton	21.0	Commission fee of the disposal of impurities, mainly. Disposal cost of sludges and wastewater is also included. These wastes are treated by a contract with a waste management company

Remark: All σ values were assumed as 0.1 μ. for model calculations unless otherwise noted

from the 40-tons/day commercial plant by Sapporo Plastic Recycle, Co., Ltd., a survey on the containers and packaging law, and interviews from some experts of pyrolysis plants. The total business balance was calculated using 17 parameters, which were assumed to fluctuate randomly along the normal distribution for a business period of 20 years. The probability of success was obtained by the Monte Carlo method with 3000 calculations using the fluctuating parameters in Table 1. For *P1*, 30 tons/day is an example of a planned value, because there were three commercial plants in the scale of 20 and 40 tons/day in Japan for plastic waste collected from households under the containers and packaging law. All the other parameters are typical values obtained from reports and interviews. For *P4*, *P5*, *PT*, and *PR*, the values were determined based on the literature [8], For *P6*, a 30% discount on heavy oil price is assumed, and the average price of heavy oil, 0.648 (USD/L), was based on a nationwide survey conducted by the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry from January 2013 through April 2019. *P1* (566 USD/ton) was given by 647 (USD/ton) × (1 – discount rate/100)/0.80 (kg/L) with a discount rate of 30% at

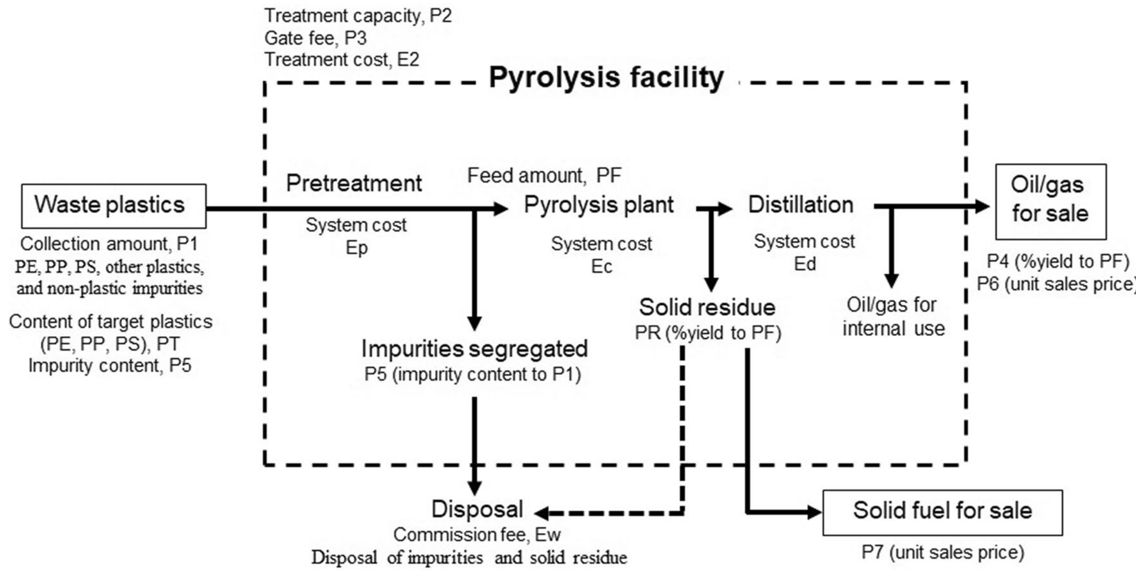

Fig. 2 Block diagram of fuel-production process and typical parameters for economic feasibility

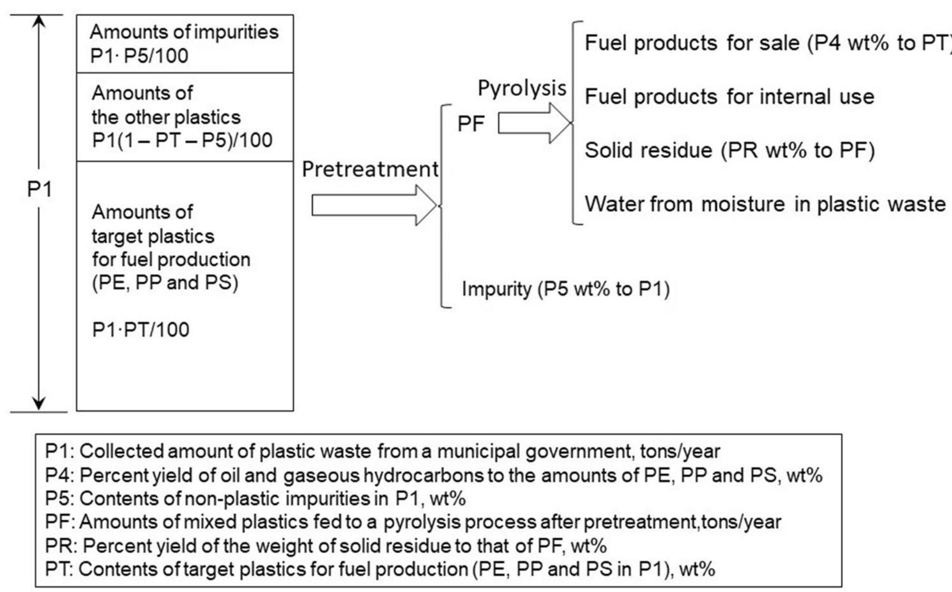

Fig. 3 Definition of the parameters of material amounts

1 USD = 107 Yen. A standard deviation of 10% from the baseline values in Table 1 was assumed for model calculations by the probabilistic approach, although σ values of some parameters are available as mentioned in the subsection "actual distribution of some parameters."

Financial parameters were treated as constant values without inflation throughout the whole business period to simplify the calculation and for easy observation of the parameter effects on the total economic balance. Equation (1) expresses the annual income (*Ai*). The typical product is pyrolysis oil; however, off-gas is a potential fuel source for the pyrolysis facility, or it can be sold to neighboring factories. A carbonaceous by-product is obtained as a pyrolysis residue, which can be sold as solid fuel depending on the business conditions. Equation (4) give annual expense (*Ae*). Annual management cost is a fixed cost, which is assumed to remain constant throughout the business period. The other terms in Eq. (4) are variable costs, which change according to the amount of plastics fed into the reactor. Annual balance *Ab* in Eq. (7) is equals to *Ai* – *Ae*. Initial expense (*Ie*) is the investment for facility construction and equipment installation. The business owner may need additional investments

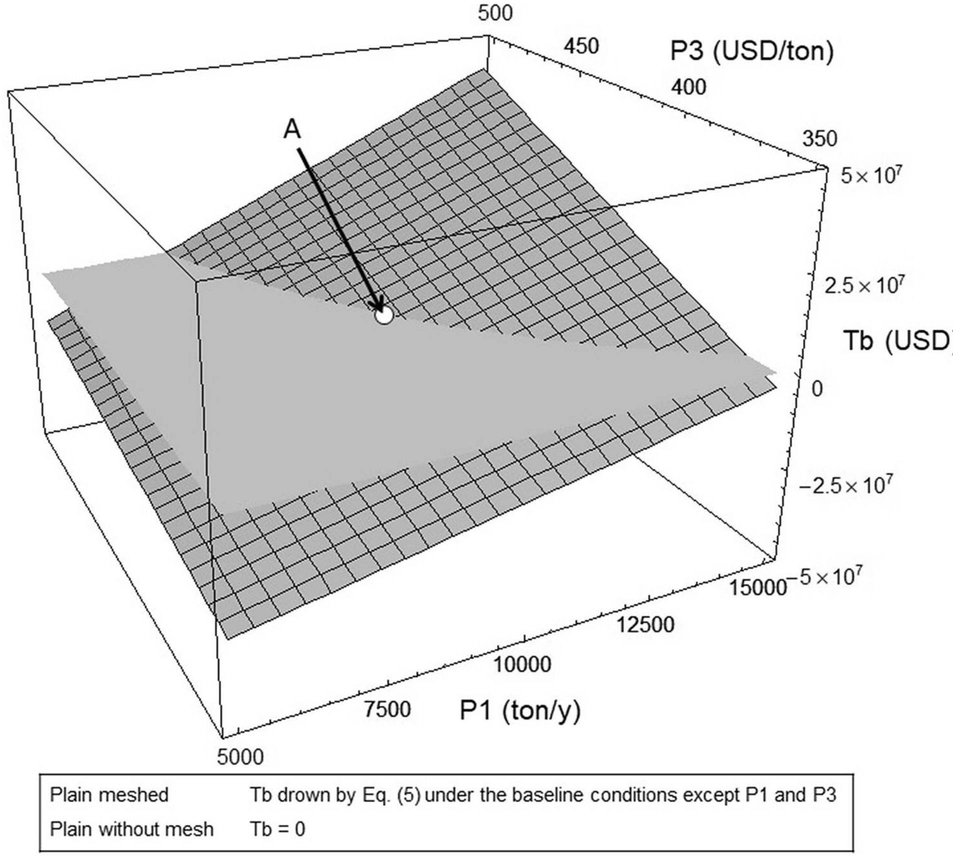

Fig. 4 Total balance, *Tb*, of the business for 20 years changing with *P1* and *P3*

for land development, for example. The total balance (*Tb*) from plastic waste pyrolysis for n years, expressed by Eq. (10). The coefficient 1.1 in Eq. (10) is a safety rate considering the additional expense for modification of major equipment as opposed to regular maintenance and repair.

$$Ai = \text{Income by gate fee} + \text{Sales profit of products} \tag{1}$$

$$= P1 \cdot P3 + P1\left(\frac{PT}{100}\right)\left(\frac{P4}{100}\right)P6 + PF \cdot P7 \cdot \left(\frac{PR}{100}\right) \tag{2}$$

$$= P1\left(P3 + \frac{P7 \cdot PR}{100} + \frac{P4 \cdot P6 \cdot PT - P5 \cdot P7 \cdot PR}{10000}\right) \tag{3}$$

$$\begin{aligned} Ae = {} & \text{Operation cost of pretreatment} \\ & + \text{Disposal cost of impurities segregated} \\ & + \text{Operation cost of pyrolysis} \\ & + \text{Annual management cost} \end{aligned} \tag{4}$$

$$= P1 \cdot E1 + P1 \cdot Ew\left(\frac{P5}{100}\right) + PF \cdot E2 + Em \tag{5}$$

$$= P1\left[E1 + E2 + \left(\frac{P5}{100}\right)(Ew - E2)\right] + Em \tag{6}$$

$$Ab = Ai - Ae \tag{7}$$

$$\begin{aligned} = {} & P1\left(P3 - E1 - E2 + \frac{P5 \cdot E2 + P7 \cdot PR - P5 \cdot Ew}{100}\right. \\ & \left. + \frac{P4 \cdot P6 \cdot PT - P5 \cdot P7 \cdot PR}{10000}\right) - Em \end{aligned} \tag{8}$$

$$Ie = Ec + Ed + Ep \tag{9}$$

$$Tb = n \times Ab - 1.1Ie \tag{10}$$

$$\begin{aligned} = {} & n\left[P1\left(P3 - E1 - E2 + \frac{P5 \cdot E2 + P7 \cdot PR - P5 \cdot Ew}{100}\right.\right. \\ & \left.\left. + \frac{P4 \cdot P6 \cdot PT - P5 \cdot P7 \cdot PR}{10000}\right) - Em\right] \\ & -1.1(Ec + Ed + Ep) \end{aligned} \tag{11}$$

Economic feasibility studies often use scenario analyses with several fixed parameters to confirm the profitability of the investment by the estimated values such as NPV and ROI of a project. In this paper, we show the economic feasibility of one scenario of fuel-oil production from plastic waste, but with several parameters that varied along the normal distribution, to indicate the probability of business success *Ps*, meaning a positive *Tb* value after 20 years. Sensitivity analysis [23, 24] of the business demonstrates the effect of each parameter on *Tb*.

For *Tb* calculations in Eq. (5) and the sensitivity analysis, each parameter is assumed to fluctuate randomly along the normal distribution. For example, Microsoft Excel can generate randomly varying each of 17 parameters using NORMSINV(RAND()) $\times \sigma + \mu$, whereμ is the mean and σ the standard deviation. *Tb* values were obtained using Eqs. (1) through (11) with the parameters fluctuated along the normal distribution. A probability density curve of *Tb* was drown using the mean value and deviation of those *Tb* values. Then, the probability of success *Ps* in 0–1, that is, percent probability in 0–100%, was obtained as the cumulative density of the probability of *Tb* being greater than zero.

For sensitivity analysis on the total balance *Tb*, in the subsection "Probability of business success and sensitivity analysis," σ is assumed to be 10% of μ for each parameter. For *P1*, for example,μ is equal to 9900 tons/y and σ is 990 tons/y. For a precise assessment of a business plan and the planned technology, the values of μ and σ can be determined by a statistical survey or from information on known commercial technologies.

Results and discussion

Probability of business success and sensitivity analysis

This study calculated the total business balance after a long-term business period rather than the cash flow in each fiscal year. Among the parameters listed in Table 1, waste collection amount *P1* and gate fee *P3* are essential for running the business. For a recycler, *P1* is important, because the business scale is directly related to the profit. *P3* is a primary concern for those who pay for recycling activities; indeed, they would want to reduce the payment. *P3* is also important for the recycler, because it determines the annual profit, as shown in Eq. (3).

Figure 4 shows that *Tb*, the total business balance after 20 years, changes with *P1* and *P3*, where the other parameter values remain fixed to the baseline values of μ in Table 1 with each $\sigma = 0$. The meshed plain shows a 3D graph of Eq. (11). *P1* changes from 5000 to 15,000 tons/y, and *P3* from 350 to 500 USD/ton. The plain without mesh is $Tb = 0$.

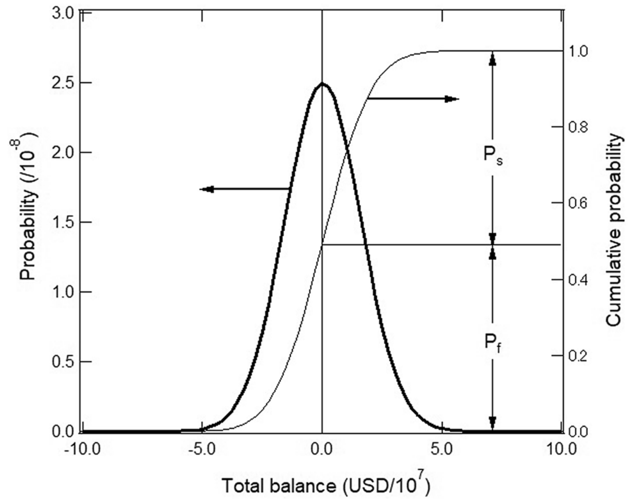

Fig. 5 Probability density curve and cumulative probability of the baseline case in Table 1

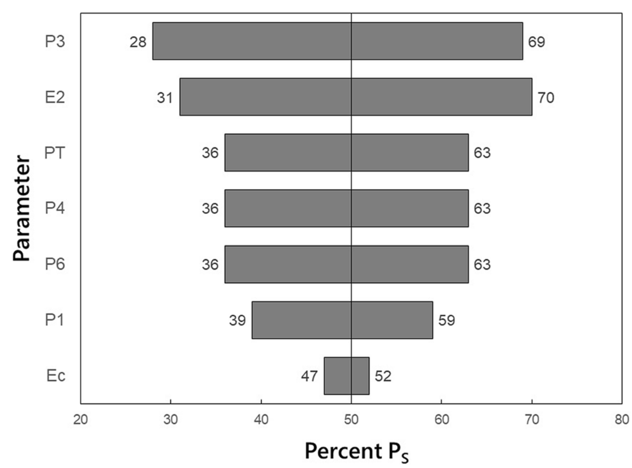

Fig. 6 Percent *Ps* with changing each seven parameters to the values of plus and minus ten percent

The two lines intersect at the break-even point of the 20-year business. Plot A is the baseline case, where $P1 = 9{,}900$ tons/y, $P3 = 434$ USD/ton, and $Tb \simeq 0$. Figure 4 indicates that *Tb* is always positive in the plane above the break-even point with *P1* and/or *P3* higher than the baseline values.

In reality, depending on the business environment, the parameters in Table 1 often fluctuate due to technical, social, and economic conditions over a long business period. Both profit and expenses are distributed from negative to positive values. At point A in Fig. 4, when each parameter was assumed to fluctuate following the normal distribution with meanμ and standard deviation of $\sigma = 10\%$ of μ, the probability density curve of *Tb* forms a normal distribution curve, shown as the bold line in Fig. 5. The probability is highest at $Tb = 0$. The total area under the curve is equal to 1.

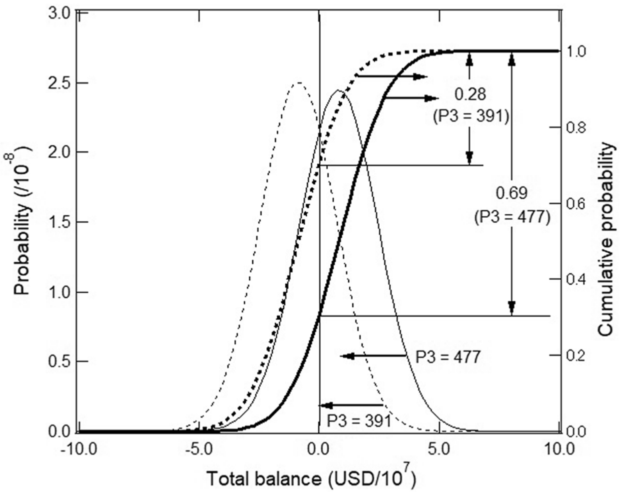

Fig. 7 Probability density and cumulative probability curves in the cases of + 10% (*P3* = 477) and – 10% (*P3* = 391) to the original *P3*

The narrow line is the cumulative probability. At *Tb* = 0, the cumulative probabilities of business success (*Ps*) and of business failure (P_f) are both 0.5, which implies a 50% probability that the total balance after 20 years will be positive.

We conducted a sensitivity analysis to examine the sensitivity of *Tb* to each parameter and find the influential parameter *Ps*. Seven parameters were examined by replacing each original value with a 10% higher or lower value. The parameters examined and the *Ps* values obtained are listed in the electronic supplementary material (see ESM_Table 3). Figure 6 shows percentage *Ps* values of μ and σ for each parameter replaced. Among the seven parameters examined, the most influential was *P3*. For example, 1.1μ (477 USD/ton) and σ=0.11μ (47.7 USD/ton) were applied to *P3* (Fig. 7). Setting the other parameters to the same values as in Table 1 and performing 3000-times calculations with random values along the normal distribution provided a probability density curve, and the cumulative density with a percentage *Ps* of 69% improved by 19% over *Ps*, obtained by the original *P3* of μ = 434 USD/ton. When 0.9μ (391 USD/ton) and σ = 0.09μ (39.1 USD/ton) were applied to *P3*, *Ps* decreased to 28%.

In Eq. (2), annual income *Ai* has the second term multiplying *P1*, *PT*/100, *P4*/100, and *P6*. Because of this term, each of *PT*, *P4*, and *P6* equally contributes to the moderate influence on total balance *Tb* as in Fig. 6. For example, a 10% change in *PT* is equivalent to a 10% change in one of the others, since (1.1 *PT*) (*P4*/100) *P6* = *PT* (1.1 *P4*/100) *P6* = *PT* (*P4*/100) (1.1 *P6*). This equation suggests that 1) social efforts to achieve separate disposal from houses, which would increase the contents of PE, PP, and PS, the major sources of fuel-oil, will contribute to income, 2) technical efforts to increase the product yield (*P4*) will contribute to income, 3) business efforts to increase sales price of the product (*P6*) contributes to income, and finally, 4) all the efforts equally contribute to income although business owners often feel that technical or engineering issues (related to *P4*) are more significant than business efforts (related to *P6*) and the accuracy of separate disposal by households (related to *PT*).

In summary, the results of the sensitivity analysis in Fig. 6 show that gate fee *P3* is the most influential parameter on the total business balance (41% difference = 69 – 28%*Ps*), and unit pyrolysis cost *E2* is the second-most influential parameter (39% difference = 70 – 31%*Ps*). These results indicate that *P3* should be carefully determined in actual business settings, and that reduction in *E2* is important to improve the total balance. The parameters *P1*, *P4*, *P6* and *PT* make the same contribution to the annual income *Ai*, because these parameters were multiplied with each other in the second term in Eq. (2). Similarly, the parameters *P7*, *PF*, and *PR* make the same contribution to *Ai*.

Comparison of the probabilistic approach to *Ps* with the conventional balance calculations

The probabilistic approach to economic feasibility using distributed parameters indicates business risks by *Ps*. On the other hand, the conventional calculation using fixed parameters provides only the business balance. Table 2 compares the probability of success in five cases as estimated

Table 2 Parameters and percent Ps in the probabilistic approach compared with conventional balance calculations

Calculation method	Case no.	Parameter				Percent P_S
		P1 μ, σ	*P3* μ, σ	*E2* μ, σ	Others μ, σ	
Probabilistic approach	1	11,000, 1100	434, 43.4	400, 40.0	Tab1, 0.1μ	62
↑	2	11,000, 1100	434, 0	400, 0	Tab1, 0	87
↑	3	11,000, 0	434, 43.4	400, 0	Tab1, 0	70
↑	4	11,000, 0	434, 0	400, 40.0	Tab1, 0	70
Conventional calculations	5	11,000, 0	434, 0	400, 0	Tab1, 0	100

Tab1 means the same μ values as in Table 1

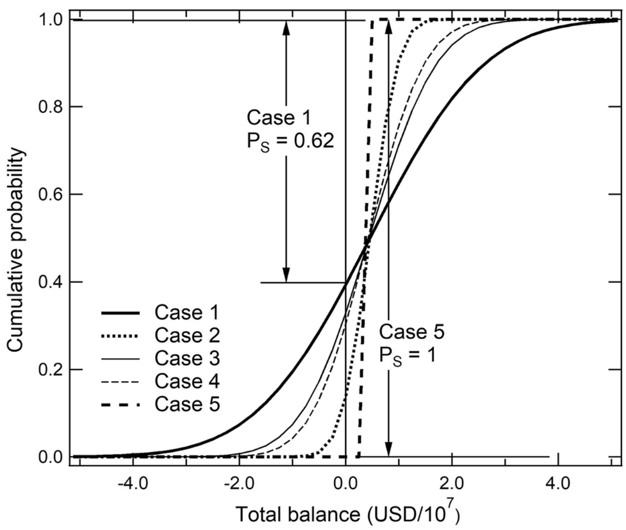

Fig. 8 Cumulative probability of cases 1–4 by the probabilistic approach compared with case 5 by the conventional balance calculation

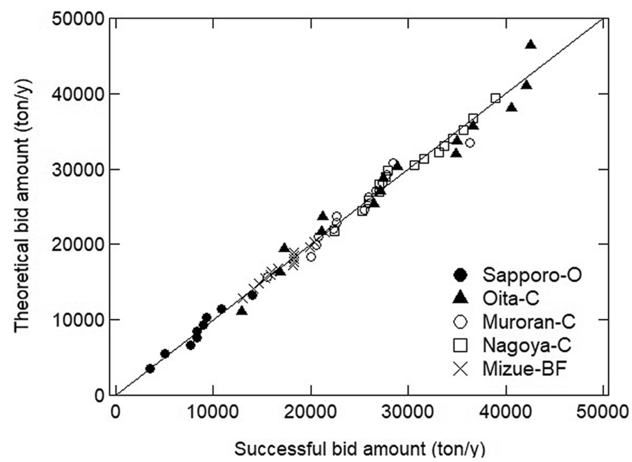

Fig. 9 Examples of successful bid amounts following to the normal distribution y = x

by the two methods. For example, the conventional balance was calculated using *P1* = 11,000 tons/year, *PF* = (1 – P5/100) = 10,780, and all the other parameters were equal to the μ values in Table 1. *Tb*, at 4.1×10^6 USD, was a positive balance although a business owner may not be satisfied with it. It also means that percentage *Ps* = 100%. On the other hand, the probabilistic approach was conducted in four cases with some parameters fluctuating along the normal distribution and some remaining fixed during the business period. Case 1 used *P1* at μ = 11,000 and σ = 1100 as well as *PF* at μ = 10,780 and σ = 1078; all the other parameters were set at the same fixed values asμ in Table 1 with σ = 0. The percentage probability of success was set at 62%. Figure 8 shows that *Ps* changed readily when the deviation σ of a parameter was chosen withμ. As shown in Fig. 6, business balance *Tb* is sensitive to parameter *P3* and *E2*. When *P3*, *E2*, and the others did not fluctuate during the business period (Case 2), *Ps* was 87%, much higher than *Ps* = 70 in cases 3 and 4, where only one of these two parameters, *P3* or *E3*, did not fluctuate.

Based on the conventional calculation of business balance in Case 5, a business planner may optimistically decide to start the business. However, the probabilistic approach shows only 62% probability of success. This result will lead a business planner to reconsider the business plan, estimating each parameter more accurately based on technical countermeasures or reliable deals in business.

Actual distribution of some parameters

Many natural phenomena, social observations, and so on, are known to follow the normal distribution due to the central limit theorem. We estimated the probability of business success and conducted a sensitivity analysis assuming that every parameter fluctuates. The fluctuation does not always follow the normal distribution or any continuous distribution. However, the normal distribution is simpler to use than models based on a combination of parameters, especially when the fluctuation pattern is not known.

Data for a Q–Q (quantile–quantile) plot—a graphic tool to compare two sets of data—were collected for some parameters. We plotted the observed data along with the theoretical values, namely, expected values calculated from the normal distribution, and distributed the plots on the y = x line. The observed data were then normally distributed.

Under the containers and packaging recycling law in Japan, two groups of recyclers bid for the contract with the Japan Containers and Packaging Recycling Association, the management organization, to receive plastic waste from households in each municipality. In the first round, registered business operators of mechanical recycling plants participate in the bidding. Feedstock recycling operators bid in the second round. ESM_Table 4 summarizes the successful bid results for some feedstock recyclers by year. The table lists the annual amounts of mixed plastics other than PET bottles and white Styrofoam trays that each recycler accepted from municipalities. The bidding data are annually published by the Japan Containers and Packaging Recycling Association. The bidding data since 2009 are available on its Internet site [25].

Figure 9 shows the Q–Q plot of successful bid amounts for five recyclers under the containers and packaging recycling law in Japan. The recycling plants operated by Nippon Steel at Muroran (μ = 24,574, σ = 4669, σ/μ = 0.19), Nagoya (μ = 30,542, σ = 4649, σ/μ = 0.15), and Oita (μ = 28,753, σ = 9304, σ/μ = 0.32); a recycling plant of JFE Steel at Muzue (injection to a blast furnace, μ = 17,228,

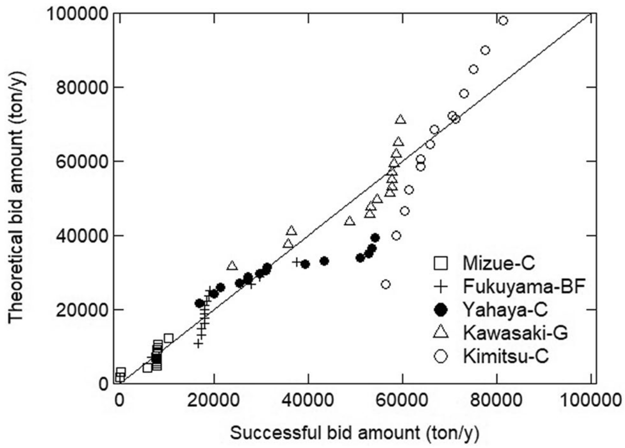

Fig. 10 Examples of successful bid amounts not following to the normal distribution y = x

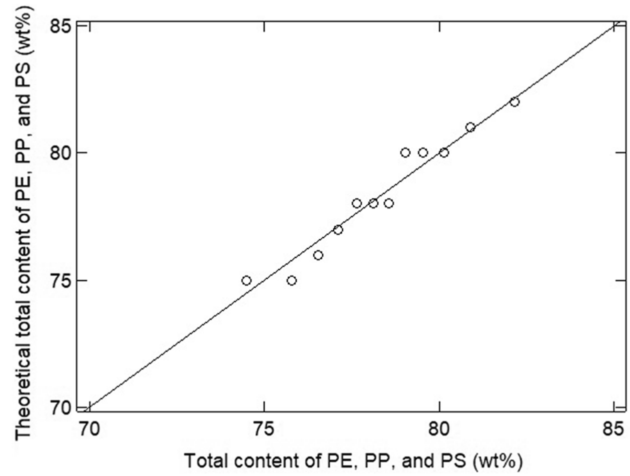

Fig. 12 Q–Q plot of the total content of PE, PP, and PS of plastic waste from households in Isezaki City, Japan

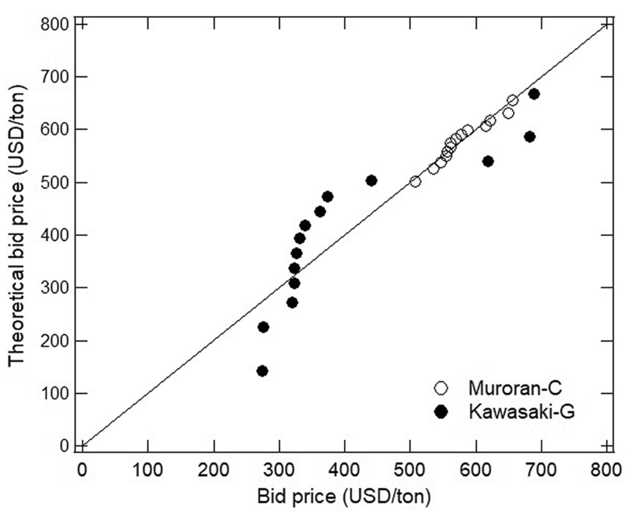

Fig. 11 Q–Q Plot of bid price of two recyclers under the containers and packaging law

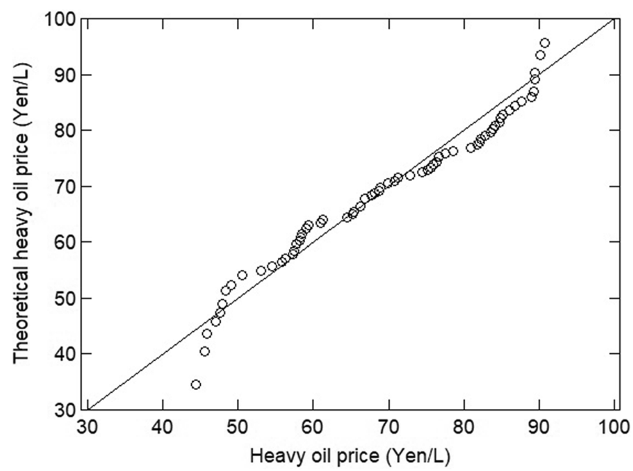

Fig. 13 Q–Q plot of the average heavy oil price in Japan

σ =2332, σ/μ = 0.14); and a fuel-oil production facility of SPC (μ = 8435, σ = 2888, σ/μ = 0.34) received plastic waste from municipalities. The annual amounts of plastics received were plotted along with the expected values, or theoretical values based on the normal distribution. The annual amounts received agreed with the theoretical values, indicating that the annual amounts received by each recycler followed the normal distribution. However, not all cases follow the normal distribution, as shown in Fig. 10. In particular, successful bids were observed in the narrow range for Showa Denko at Kawasaki (syn-gas production through gasification, μ = 51,452, σ = 10,426, σ/μ = 0.20), JFE-Mizue (cokes-oven treatment, μ = 6941, σ = 2791, σ/μ = 0.40), and JFE-Fukuyama (injection to a blast furnace, μ = 19,967, σ = 6788, σ/μ = 0.34). These results show that not only did the recyclers receive stable amounts in multiple years but that the business balance of each recycler was stable. The reason for the stable amounts in the bidding is not clear. The bidding may not be competitive in some municipalities. After many years, the bidding tactics of each recycler might be well established. Notably, narrow ranges of bid amounts have been observed for the Kawasaki and Mizue-Cokes oven in recent years, and successful bid amounts are usually low in the early years, as shown in ESM_Table 4. This suggests possible changes or fluctuations in the bid amounts during the business periods, as well as startup and business continuity difficulties with respect to *P1* under the law.

Figure 11 shows a Q–Q plot of successful bid prices corresponding to *P3*, provided by two recyclers. The prices provided by Nippon Steel at Muroran (μ = 62,216, σ = 4445, σ/μ = 0.07) were distributed along the normal distribution. However, the prices of Showa Denko at Kawasaki ($\mu = 43{,}622$, $\sigma = 15{,}086$, $\sigma/\mu = 0.35$) do not follow the normal distribution. The reason for the different trends between the two recyclers is not clear. This could provide another theme in socioeconomic studies for the promotion of the recycling business.

Figure 12 shows a Q–Q plot for three types of thermoplastics, PE, PP, and PS, a major source of liquid hydrocarbon, based on data in ESM_Table 5 [26]. The contents follow the normal distribution ($\mu = 78.3$, $\sigma = 2.2$). The plastic contents corresponding to *PT* were stable, because the σ/μ ratio (given $\mu/\sigma = 0.02$) was much smaller than the *P1* and *P3* values under the containers and packaging recycling law mentioned above.

A recycling business has two sources of income: waste treatment charges collected from waste generators and profit on sale of the recycled product. The essential income parameters are gate fee, *P3*, unit price of waste treatment, and *P6*, unit price of the product. In fuel sales, heavy oil price could be a typical reference to determine the unit sales price of fuel products from plastic waste. The monthly prices of heavy oil in Japan during January 2013 to May 2019 were analyzed by the Q–Q plot in Fig. 13 based on Japanese government reports [27]. The statistical values were $\mu = 567$, $\sigma = 14.3$ USD/ton, and $\sigma/\mu = 0.03$. The fluctuation based on σ/μ seems low compared with other parameters such as *P1* and *P3*. However, unit sales price, *P6*, should be carefully determined, because *Tb* is sensitive to *P6*, similar to *PT* and *P4*, as in Fig. 6.

Conclusions

This paper proposed a probabilistic approach to evaluate economic feasibility. The parameter values of a baseline model were based on the literature or determined from interviews. In contrast to the conventional case study method of using a few sets of fixed values as the parameters for balance calculation, our model employed parameters that fluctuated along the normal distribution. A probability density curve of the total balance was obtained from the fluctuating parameters. The curve provides the probability of business success *Ps*, meaning a positive total balance after a business period.

In the case of the baseline model, *Ps* was about 50%. The conventional method of using fixed parameters can provide a business balance, but it yields little information about business risks even if the business balance obtained in the case studies is positive. A business at 50%*Ps* would not be sustainable. Sensitivity analysis measures the influence of each parameter on *Ps*.

Indeed, some parameter values change under actual conditions during a business period. Sensitivity analysis was conducted for each parameter to show the strength of its effect on the total balance (or the sensitivity of the total balance to a change in a parameter value). To start a technology-based business, a business planner often focuses on technical achievements such as product yield. However, economic conditions such as gate fee and social conditions such as amount of waste collection are also important, and sometimes critical to the economic balance of the business. Under the baseline conditions, the most influential parameter on the total balance *Tb* was the gate fee *P3*, followed by the unit pyrolysis cost *E2*. When the mean value of *P3* is 10% higher or lower than the baseline value, *Ps* is 69% and 28%, respectively. When *E2* is 10% higher or lower than the baseline value, *Ps* is 31% and 70%, respectively. Meanwhile, the pyrolysis plant cost *Ec* has a limited influence on the total balance. When *Ec* is 10% higher or lower than the baseline value, *Ps* is 52% and 47%, respectively. In other words, the sensitivity analysis under baseline conditions showed that *P3* and *E2* are the most effective parameters to increase *Ps*. These results provide important information for business planners and operators, who should prioritize higher mean values and lower deviations of the gate fee paid by waste generators and to lower mean values and deviations of the operation cost of the pyrolysis process.

The probability of success of a business can be accurately estimated if suitable μ and σ values are obtained. Efforts to determine such values constitute the first step in the sustainability assessment of a business plan. It may not be easy to fix each parameter value under new business conditions. We can estimate the business risks by the probabilistic approach with sensitivity analysis using distributed parameters even if fluctuation pattern is not known.

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