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Variability-based optimal design for robust plastic recycling systems

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ABSTRACT

The demand for recovered materials affects the profitability of the recycling processes and at the same time is susceptible to changes in external factors such as resource prices. Therefore, variability of such external parameters should be considered, when designing a recycling system. In this study, we develop a framework for the variability-based optimal design of plastic recycling for constructing a robust recycling system over external changes in the market such as fluctuations of material prices. The subject of this study is a sorting facility of post-consumer plastics equipped with automated sorting machines. The gross operating profit (GOP) is formulated based on a process model of the plastic sorting facility, internal and external parameters such as recovery ratios and sales prices of recovered plastics by resin type. By combining integer programming and Monte Carlo simulation, we obtain the potential optimal solutions that can maximize the GOP depending on the variability of plastics sales prices and their correlations between resin types, which are estimated based on the statistics for the interval between 2007 and 2011. Distributions of the optimal solutions and variability of the GOP are visualized according to the import price of naphtha for supporting decision-makers to determine resin types that should be recovered. Based on the results, we recommend the solution where polyethylene, polypropylene, and polystyrene are recovered. Moreover, the recommended solution is validated with the observed sales prices of plastics by resin type between 2012 and 2014.

1. Introduction

In the conventional recycling system in Japan, household waste plastic containers and packaging are separated at source, and then waste collectors (municipalities have the responsibility for collection of household waste) remove alien substances through magnetic and manual separation processes before handing off waste plastics to recyclers. Moreover, the recyclers separate the targeted resin types, which are usually polyethylene (PE) and polypropylene (PP), from other resin types through a series of separation processes including flotation. Primarily aiming to resolve the redundancy due to overlapping investment on those double sorting processes as well as to recover other resin types such as polystyrene (PS) and polyethylene terephthalate (PET), introduction of integrated plastic sorting facilities that assort waste plastics by the resin type was recently proposed (JCPRA, 2014).

Recycling has a dual function, i.e., waste treatment and production of recycled materials. Therefore, we need to consider not only input-side external parameters such as resin composition of waste plastics but also output-side external parameters that possibly influence the economic efficiency or profitability of a recycling system. In particular, the demand for recovered materials affects the profitability and at the same time is susceptible to changes in external factors such as resource prices, including oil price. In this context, besides the possibility of improvement in the economic efficiency, the plastic sorting facility could enhance the robustness of a recycling system over variable external parameters. To achieve such purposes, resin types that should be assorted and recovered need to be adequately selected in view of the variability of the plastics sales prices by resin type, which are possibly mediated by the oil price. Therefore, it is necessary to develop a decision support method for determining which resin types should be recovered and how many sorting machines should be installed, considering external changes in the market.

Numerous studies have performed economic or environmental optimization of reverse logistics, disassembly, and recycling of waste products using linear programming (LP), integer programming (IP), mixed-integer linear programming (MILP), goal programming, or other optimization models. Each of these studies optimized one or multiple objectives, including not only the recycler's profit or costs (Kilic et al., 2015; Lu et al., 2006; Simic and Dimitrijevic 2012; Tang et al., 2008; Wang et al., 1995; Williams

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et al., 2007) but also the product quality (Nakatani and Hirao 2011; Pati et al., 2008), inventory fluctuations (Vadde et al., 2011), maximum working hours of drivers (Ramos et al., 2014), recycling rates (Shi et al., 2014), the quantity of reused items (Chung et al., 2016), and environmental impacts such as carbon dioxide (CO_2) emissions (Hara et al., 2007; Komly et al., 2012; Ramos et al., 2014; Tsai and Hung 2009; Vadenbo et al., 2014). Some studies considered the variability or uncertainty of parameters such as the quantity of waste products and demands for recovered products (Ameli et al., 2016; Ayvaz et al., 2015; Francas and Minner 2009; Franke et al., 2006; Kongar and Gupta 2006; Simic 2015; Zhou and Zhou 2015). Simic and Dimitrijevic (2013) developed a risk-explicit interval LP model, which considered the sorting and allocation of metals for long-term planning in vehicle recycling factories, and maximized profit and minimized decision risk by considering upper and lower bounds of respective parameters including revenues from sales of sorted metals. Simic (2016) proposed an interval-parameter two-stage stochastic full-infinite programming model, which could efficiently handle multiple external uncertainties for end-of-life vehicles management systems. Such optimization modeling integrated with a variability analysis of relevant parameters can be applied to recycling systems for different kinds of waste, including plastic waste. Furthermore, as mentioned above, the relationships between external parameters under a common determinant factor, i.e., plastics sales prices of different resin types, which could be mediated by the oil price, should be taken into account and should be examined for the optimal design of plastic sorting facilities. If such correlated parameters are assumed to independently fluctuate in the variability or uncertainty analysis (e.g., Monte Carlo simulation), optimal solutions could also be obtained from unrealistic combinations of parameter values, which become a noise for decision-making. However, none of the previous studies that aimed to optimize waste recycling or sorting processes considered correlations among different variable parameters in the variability or uncertainty analysis. Therefore, it is necessary to develop a framework that incorporates relational analysis of variable external parameters with optimization modeling.

In this study, we aim to develop a framework for the variability-based optimal design of plastic recycling for constructing a robust recycling system over the external changes in the market such as fluctuations of material prices. The subject of this study is a sorting facility of post-consumer plastic containers and packaging, equipped with automated sorting machines with near-infrared sensors that detect and sort out the targeted resin types from other types. Further, we analyze fluctuations in plastics sales prices by resin type and incorporate their correlations into a Monte Carlo simulation-based optimization. Here, Colicchia and Strozzi (2012) defined robustness as the ability of the system to “maintain the function unchanged, or nearly unchanged, when exposed to perturbations,” and Han and Shin (2016) gave a similar definition to robustness. In this paper, we focus on the stability of the profit as a basis for maintaining the above-mentioned function of a recycling system, as well as the variability of plastics sales prices and their relationships between different resin types as perturbations.

The remainder of this paper is organized as follows. First, a process model of the sorting facility that correlates the quantities of recovered plastics by resin type to the resin composition of waste plastics is described in terms of the functions of the automated sorting machines. We select the profitability of the sorting facility that is measured by the gross operating profit (GOP) as an objective function for optimization. The GOP is formulated based on internal and external parameters such as resin composition of waste plastics, recovery ratios of plastics by resin type, investment and operation costs of sorting machines, the quantities of recovered plastics by resin type, and their sales prices. Subsequently, IP-based optimization of sorting processes that maximize the GOP is performed to determine which resin types should be recovered from waste plastics. As an approach to the robust design of the sorting facility, we develop a framework for variability analysis using Monte Carlo simulation combined with IP-based optimization. Here, the relationship between sales prices of plastics by resin type and the import price of naphtha, which is considered a determinant factor of plastics sales prices, is analyzed based on the statistics for the interval between 2007 and 2011. Then, normally-distributed random numbers for sales prices of each resin type are generated according to the import price of naphtha. Then, we comprehensively obtain the potential optimal solutions that can maximize the GOP depending on the variability of plastics sales prices. The distributions of the optimal solutions and variability of the GOP are visualized according to the import price of naphtha for supporting decision-makers to determine resin types that should be assorted. We discuss the results and provide a recommendation on how many sorting machines should be installed and which resin types should be recovered for a robust recycling system. Moreover, the recommended solution is validated with the observed sales prices of plastics by resin type between 2012 and 2014. Finally, we conclude by discussing implications and limitations of this study.

Table 1
Default values for the recovery ratios of plastics by resin type in the sorting facility.

LDPE (T)	LDPE (C)	HDPE (T)	HDPE (C)	PP (T)	PP (C)
0.40	0.50	0.50	0.60	0.20	0.30
PS (T)	**PS (C)**	**PET (T)**	**PET (C)**	**PVC/D**	
0.30	0.40	0.50	0.60	5.00	

Note: A recovery ratio is defined as the ratio of the quantity of recovered plastics to that of waste plastics by resin type. When color sorting is not performed, the recovery ratio of each resin type is equal to that of (C). When LDPE and HDPE are not assorted, the recovery ratio of PE is equal to that of HDPE. (T) denotes transparent and (C) denotes colored plastics. These values are assumed based on demonstration experiments conducted in a plastic sorting facility.

2. Material and methods

2.1. Process model of the plastic sorting facility

A process flow diagram of the plastic sorting facility assumed in this study is illustrated in Fig. 1 with reference to those experimentally operating in Japan. We aim to determine which resin types should be recovered, and consequently we can specify which processes in Fig. 1 are necessary or unnecessary among the full sorting processes.

According to the process flow, a process model of the sorting facility was described based on the functions of the automated sorting machines, e.g., recovery ratios of plastics. The quantities of recovered plastics by resin type were estimated by multiplying the total throughput of waste plastics, their resin composition, and the recovery ratios by resin type. At the last step, polyvinyl chloride and polyvinylidene chloride (PVC/D) were separated from other resin types which were treated by feedstock recycling or energy recovery afterward. The Japanese feedstock recyclers usually refuse waste plastics that contain PVC/D in significant quantities because it would harm their furnaces by generating corrosive gases such as hydrogen chloride. Therefore, to maintain the chlorine concentration in other resin types as low as possible, they were partially separated along with PVC/D.

Mixtures of other resin types with the targeted type except for PVC/D were assumed negligible, which means that the purity of any resin type of recovered plastics was considered 100%. Instead, plastics recovery ratios became relatively low, as presented in Table 1. On the other hand, the recovery ratio of PVC/D (5.00) indicates that five times as much waste plastics, including other resin types,

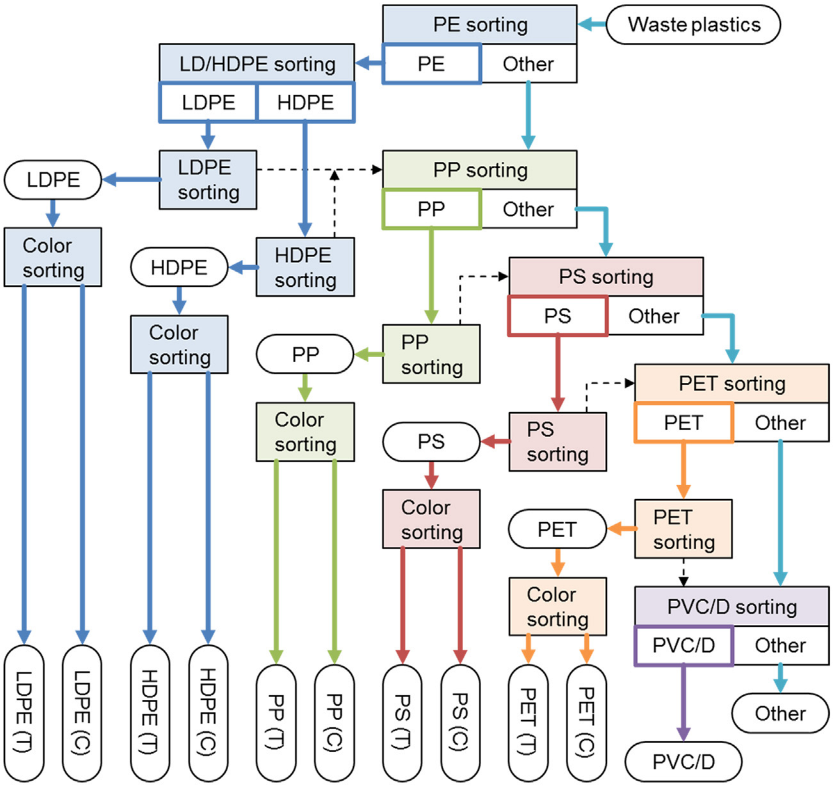

Fig. 1. Process flow diagram of the plastic sorting facility with the full sorting processes assumed in this study.
Note: Sales and import prices (monthly average) are adapted from METI (HP).

as targeted PVC/D are removed at the PVC/D sorting process. For each targeted resin type, other than PVC/D, two sorting steps were required to obtain salable recovered plastics; an additional color sorting process was required to sorted out transparent and colorless (hereinafter referred to as "transparent") plastics from colored and composite (hereinafter referred to as "colored") plastics to obtain more valuable recovered plastics.

2.2. IP-based optimization of the sorting facility

As an objective function for optimization of the sorting facility, the GOP [JPY/day], i.e., incomes after subtracting the running and capital (depreciation) costs, was formulated based on the internal and external parameters as follows:

$$\text{maximize} \quad GOP = \sum_{i=1}^{7} P_i^C \cdot Q_i + \sum_{i=1}^{5} \left(P_i^T - P_i^C\right) \cdot Q_i^T - \mathrm{E} \cdot \mathrm{H} \cdot p_E - \left(C_L + \frac{C_I}{d}\right) \cdot \mathrm{M} \qquad (1)$$

$$Q_i = S_i \cdot r_i \cdot W_i \, (\mathrm{i} = 1, \cdots, 6) \qquad (2)$$

$$Q_7 = \sum_{i=1}^{7} W_i - \sum_{i=1}^{6} Q_i \qquad (3)$$

$$Q_i^T = S_i^T \cdot r_i^T \cdot W_i^T \qquad (4)$$

$$H = \sum_{i=1}^{5} S_i \cdot h + \sum_{i=1}^{6} S_i \cdot \frac{W_i}{s} + \sum_{i=1}^{5} S_i^T \cdot \frac{W_i}{s} \qquad (5)$$

$$M = \sum_{i=1}^{5} S_i + \sum_{i=1}^{6} S_i + \sum_{i=1}^{5} S_i^T \qquad (6)$$

subject to

$$S_i^T \leq S_i \qquad (7)$$

$$\mathrm{S}_6 = 1 \qquad (8)$$

where LDPE, HDPE, PP, PS, PET, PVC/D and the other resin types are denoted by $i = 1, \cdots, 7$, respectively. In Eq. (1), P_i^C and P_i^T denote the sales prices of recovered colored and transparent plastics of resin type i [JPY/kg], respectively. Q_i denotes the quantity of recovered plastics of resin type i, and Q_i^T denotes the quantity of recovered transparent plastics i [kg/day]. In Eq. (2), W_i denotes the quantity of waste plastics of resin type i, which is calculated by multiplying the total throughput of waste plastics (10 tons/day) by resin composition [kg/day]. r_i denotes the plastics recovery ratio of resin type i, and S_i $(i = 1, \cdots, 6)$ is a variable that becomes 1 when resin type i is recovered from waste plastics. Similarly, in Eq. (4), W_i^T denotes the quantity of waste transparent plastics of resin type i [kg/day], r_i^T denotes the recovery ratio of transparent plastics of resin type i, and S_i^T $(i = 1, \cdots, 5)$ is a variable that becomes 1 when transparent plastics of resin type i is recovered. In addition, in Eq. (1), the running and capital costs are formulated by the electricity consumption E of a sorting machine (30 kW), the total operating time H of all machines [hour/day], the electricity price p_E (20 JPY/kWh), the labor cost per machine C_L (5000 JPY/day), the investment cost of the sorting machine C_I (30 million JPY), its depreciation period d (10 years and 300 days/year), and the number of sorting machines installed to the sorting facility M. In Eq. (5), h and s denote the maximum operating time (10 h/day) and the processing speed

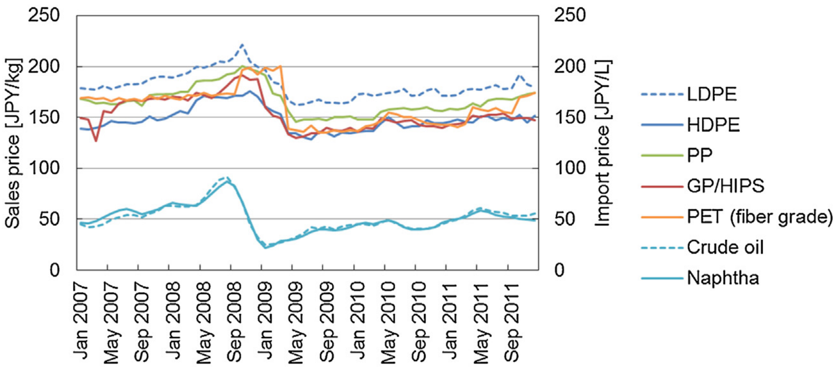

Fig. 2. Fluctuations of sales prices of virgin resin and import prices of crude oil and naphtha between 2007 and 2011.
Note: Sales and import prices (monthly average) are adapted from METI (HP).

(1000 kg/h) of a sorting machine, respectively. Moreover, Eq. (6) indicates that, as mentioned in Section 2.1, a sorting facility needs to install two machines for recovering each resin type ($i = 1, \cdots, 5$); one machine for the separation of PVC/D ($i = 6$); and another for separating transparent plastics from colored plastics for each resin type ($i = 1, \cdots, 5$).

The IP-based optimization of the sorting processes for maximizing the GOP was performed with the binary design variables S_i and S_i^T ($i = 1, \cdots, 5$) under the constraint in Eqs. (7) and (8). As shown in Eq. (8), S_6 was fixed at 1 because the Japanese plastic recyclers were required to remove PVC/D from other resin types when they handed off the unsellable waste plastics to the feedstock recyclers or to waste disposers. We assumed that separated PVC/D were treated as waste with a disposal cost of 30 JPY/kg (i.e., $P_6^C = -30$) and that other resin types were processed by feedstock recycling or energy recovery with an outsourcing cost of 10 JPY/kg (i.e., $P_7^C = -10$). Then, the results indicated how many machines should be installed and which resin types should be recovered from waste plastics.

2.3. Variability analysis using Monte Carlo simulation

Some of the above-mentioned parameters, such as P_i^C, P_i^T, W_i, W_i^T, and p_E, are susceptible to external changes. In particular, variability of such parameters in terms of multiple resin types is relevant to the profit of a plastic sorting facility. Monte Carlo simulation can analyze comprehensively combinations of multiple variables, whose variability or uncertainty is described as probability distributions. In this study, variability analysis using Monte Carlo simulation combined with the IP-based optimization is proposed, where potential optimal solutions that can maximize the GOP are comprehensively obtained considering the variability of the external parameters.

In this study, we analyzed the variability of plastics sales prices for multiple resin types, which could be susceptible to changes in external factors such as import prices of crude oil and naphtha. While the Bank of Japan publishes the monthly price index of the undifferentiated recovered plastics (BOJ HP, 2005), sales prices of recovered plastics according to resin type are not disclosed. In this study, on the basis of interviews that we conducted with Japanese plastic recyclers, we assume that sales prices of recovered plastics correlate to those of the respective types of virgin resin and sales prices of the recovered natural and general plastics are 40% and 20% of those of virgin resin, respectively.

When applying the Monte Carlo simulation, the probability distributions of relevant variable parameters need to be examined carefully. Here, the relationships among import prices of crude oil, import prices of naphtha, and sales prices of plastics (virgin resin) were analyzed based on the national statistics of Japan (METI HP, 2015). Fluctuations of monthly average sales and import prices between 2007 and 2011 are shown in Fig. 2. Consequently, the relation between crude oil and naphtha import prices was considered strong enough to assume a perfect correlation between them ($R^2 = 0.950$). Nevertheless, the variability of the plastics sales prices of requires further analysis.

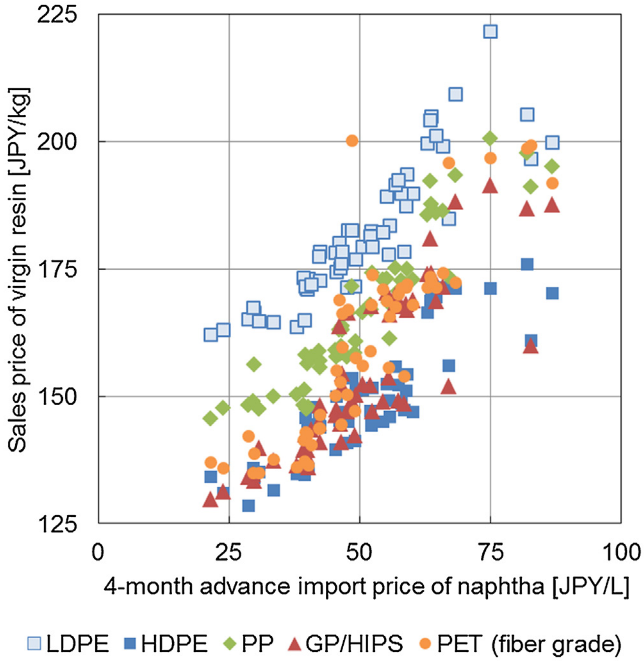

Fig. 3. Relationships between the sales prices of virgin resin and the import price of naphtha between 2007 and 2011.

The relationships between the import price of naphtha and the sales prices of virgin resin are shown in Fig. 3. We assumed that the fluctuation of sales price of each resin types was primarily determined by that of import price of naphtha as the main raw material of virgin resin, and that there were linear relationships between them. The result of regression analysis between the sales price of each type of virgin resin y and the four-month advance import price of naphtha x is presented in Table 2. The strongest correlations were found when a time lag of four months was set between the import price of naphtha and the sales prices of virgin resin. Here, the coefficient of determination, R^2, is moderately high and a regression coefficient is around 1 for each resin type (see Table 2). These results indicate that the above-mentioned assumption is partly supported but there remain variation factors in plastics sales prices.

Table 2
Regression analyses between the sales prices of virgin resin and the four-month advance import prices of naphtha.

	$\hat{y}=$	139+	$0.844x$	$R^2 = 0.788$
	(6.205)	(3.116)	(0.060)	
HDPE	$\hat{y}=$	111+	$0.745x$	$R^2 = 0.782$
	(5.579)	(2.801)	(0.054)	
PP	$\hat{y}=$	118+	$0.963x$	$R^2 = 0.860$
	(5.520)	(2.772)	(0.053)	
GP/HIPS	$\hat{y}=$	105+	$0.982x$	$R^2 = 0.734$
	(8.376)	(4.206)	(0.080)	
PET (fiber grade)	$\hat{y}=$	102+	$1.147x$	$R^2 = 0.757$
	(9.220)	(4.630)	(0.088)	

Note: $\hat{y}$ denotes the estimate of a sales price of each type of virgin resin, and x denotes the four-month advance import price of naphtha. The standard errors are given in parentheses. Two-sided p-values are 0.000 for all regression coefficients. The number of samples is 56, i.e., every month between 2007 and 2011 excluding the four-month time lag, for each resin type. Sales and import prices (monthly average) are adapted from the national statistics of Japan (METI HP).

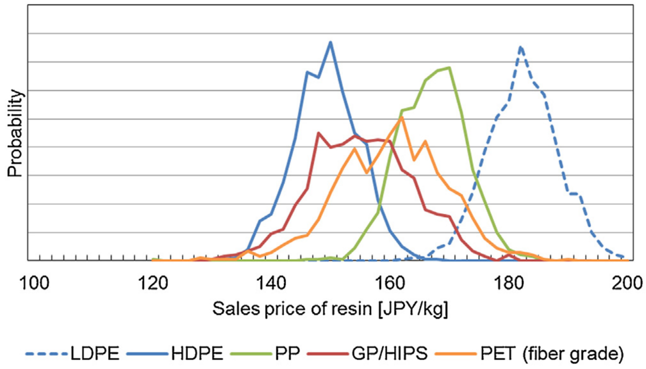

Fig. 4. Distributions of sales prices of virgin resin (four-month advance import price of naphtha: 50 JPY/L).
Note: The vertical axis indicates a frequency where each combination of resin types becomes an optimal solution by each import price of naphtha. All the optimal solutions include PVC/D separation at the last step of the sorting processes. The number of installed machines is calculated by multiplying the number of recovered resin types by two and then adding one (PVC/D separation). If a color sorting between transparent and colored plastics is included, one additional machine is installed (see Fig. 1). PET (T/C) indicates that PET is assorted into transparent and colored.

Table 3
Default values for resin composition of waste plastics treated in the sorting facility.

LDPE (T)	LDPE (C)	HDPE (T)	HDPE (C)	PP (T)	PP (C)
0.06	0.12	0.04	0.07	0.07	0.21
PS (T)	PS (C)	PET (T)	PET (C)	PVC/D	Other
0.08	0.15	0.08	0.05	0.01	0.06

Note: When LDPE and HDPE are not assorted, the recovery ratio of PE is equal to that of HDPE. (T) denotes transparent and (C) denotes colored plastics. These values are assumed based on demonstration experiments conducted in a plastic sorting facility.

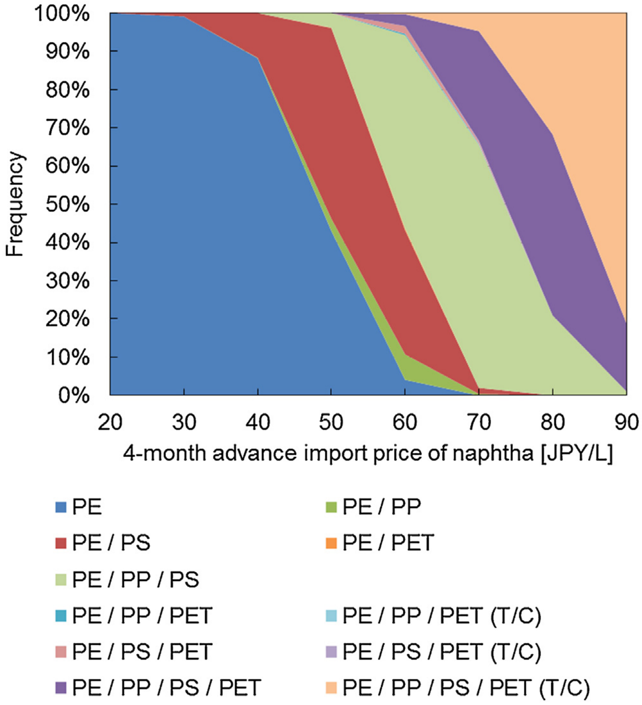

Fig. 5. Distributions of potential optimal solutions for the sorting processes according to the import price of naphtha.
Note: Ranges of the GOPs correspond to the two-sided 95% confidence intervals. All solutions include PVC/D separation at the last step of the sorting processes. The total throughput of waste plastics is assumed 10 tons/day with processing speed of 1 ton/h and operating time of 10 h/day.

Then, based on residuals of regression in Table 2 (i.e., variations of plastics sales prices that were not explained by the variability of the naphtha import price), 1000 normally-distributed random numbers for sales prices of each resin type were generated according to the import price of naphtha (20, 30, 40, . . ., 90 JPY/L). The standard errors of $\hat{y}$ were used as the standard deviation of the normal distributions for each resin type (Fig. 4). Accordingly, in total 8000 sets of random numbers for sales prices of recovered plastics were generated. The other internal and input-side external parameters were assumed constant as presented in Section 2.2, and the default values for the resin composition of waste plastics are shown in Table 3. Then, Monte Carlo simulation was applied to IP-based optimization and 1000 optimal solutions were obtained by each import price of naphtha.

3. Results

3.1. Potential optimal solutions and a recommended solution

The distributions of optimal solutions are visualized in Fig. 5 in terms of the variability of the import price of naphtha between 20 and 90 JPY/L. It is clearly shown that the optimal solutions change depending on the import price of naphtha. In addition, different optimal solutions are sometimes obtained for the same naphtha import price, because of the distribution of sales price of each resin type (see Fig. 4). This figure shows that the optimal solution where only PE is recovered is dominant if the import price of naphtha remains relatively low. On the other hand, the solutions with PE, PP, PS, and PET recovery become dominant when the import price of naphtha increases. Furthermore, in Fig. 5, there are five dominant solutions distinguished among a number of possible combinations of resin types that are recovered from waste plastics. The numbers of installed machines differ between those five solutions, i.e., 3, 5, 7, 9, and 10 machines for the respective solutions. The results indicate that we need to identify the most robust solution over the variability of the import price of naphtha, given that the outlook for the oil price is uncertain.

Variability of the GOPs for the above-mentioned five dominant solutions, according to the import price of naphtha, is illustrated in Fig. 6. Ranges of the GOPs stem from the distributions of the plastics sales prices. Overall, the GOPs show negative values, i.e., the cost of the sorting processes ranges between 6 and 13 JPY/kg. Nevertheless, these costs are still lower than those incurred by conventional plastic sorting facilities in Japan, which are dependent on manual separation processes. For example, outsourcing costs for

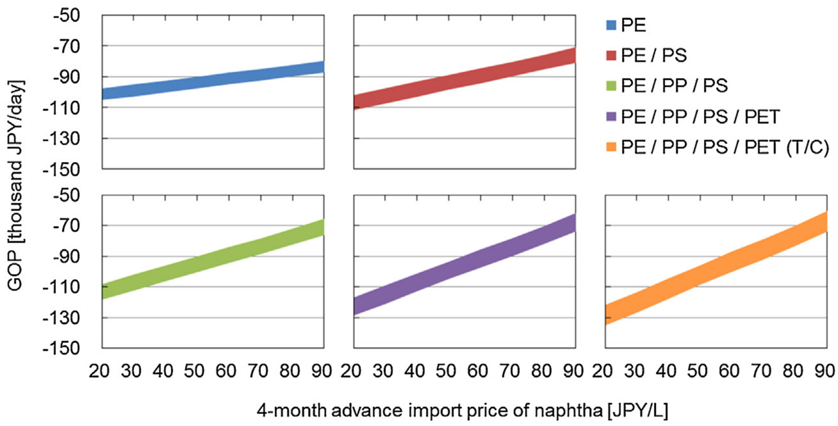

Fig. 6. Variability and ranges of the GOPs for the five dominant solutions according to the import price of naphtha.
Note: LDPE and HDPE are not assorted and are recovered together as PE. Dotted arrows show that the removed plastics from the sorting process at the root are brought back to the sorting process at the end of the arrow.

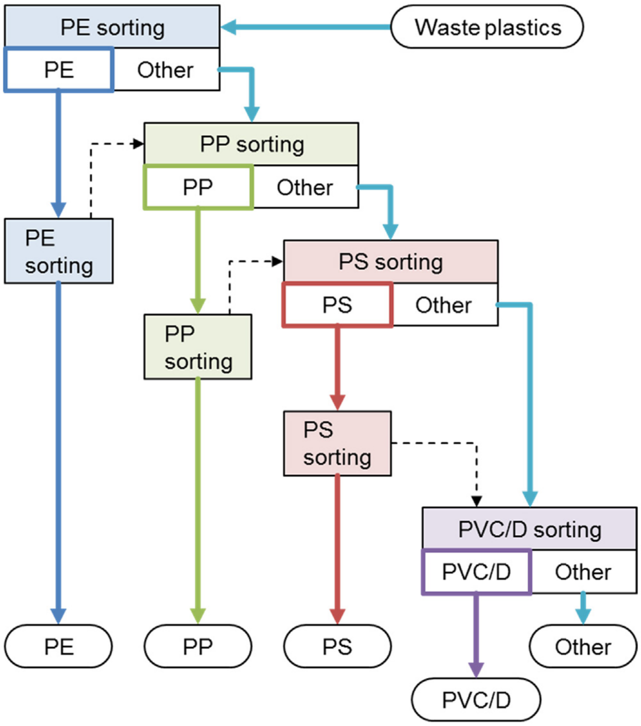

Fig. 7. Process flow diagram of the recommended solution for a plastic sorting facility (with PE, PP, and PS recovery).
Note: Import prices (monthly average) are adapted from the national statistics of Japan (METI HP).

plastic sorting facilities are between 14 and 35 JPY/kg in a specific city of Japan (Hamada, 2010).

The result shown in Fig. 6 indicates that the solutions where PE, PP, PS, and PET are recovered with 9 or 10 machines seem risky because those GOPs fall sharply with a decline in the import price of naphtha. On the other hand, the solution where only PE is recovered seems too conservative since its GOP becomes the lowest with the import price of naphtha between 70 and 90 JPY/L. Therefore, as of 2012, we recommended that seven machines should be installed with the aim of recovering PE, PP, and PS since the solution was considered the most robust in terms of stability of the GOP. A process flow diagram of this recommended solution is illustrated in Fig. 7.

3.2. *Validation of the recommended solution*

The above results depend on the relationships between the naphtha import price and plastics sales prices, which were estimated on the basis of the fluctuations in prices between 2007 and 2011. However, it is unknown whether the relationships are valid for different periods. Therefore, to validate the above recommendation, we calculate the GOPs of the potential optimal solutions using the observed sales prices of plastics by resin type for every month between 2012 and 2014 (METI HP, 2015). Fig. 8 shows fluctuations of the GOPs of the five dominant solutions. Although differences in their GOPs are small for 2012, the two solutions with recovery of PE, PP, PS, and PET stand out for 2013 and 2014 with increases in the import prices of crude oil and naphtha. On the other hand, the solutions where only PE or PE and PP are recovered miss the chance to gain a larger profit. However, the differences in the GOPs become small again with a decrease in the oil price in the latter half of 2014. The solution with recovery of PE, PP, and PS remains the first- to third-best in profitability. The results validate the idea that the recommended solution is robust over the variability of sales prices of plastics. However, it should be noted that the variations in external factors, except the prices of naphtha and plastics, are not considered, i.e., those parameters are assumed to be constant in the above-mentioned analysis. This is further discussed in Section 4.

4. Discussion

The results of the variability analysis show that the optimal solutions change depending on the import price of naphtha and that the different optimal solutions are sometimes obtained for the same import price of naphtha. In such cases, decision-makers can refer to the distributions of optimal solutions (see Fig. 5) and variability of the profit (see Fig. 6) for identifying dominant and stable solutions under variable external parameters. In particular, they can narrow down the solutions (i.e., combinations of resin types targeted for sorting) on the basis of the distributions shown in Fig. 5 and select the most economically feasible or riskless solution (depending on their business policy) on the basis of the GOP variability shown in Fig. 6. In this paper, considering the variability of the plastics sales prices, which was estimated on the basis of the statistics for the interval between 2007 and 2011, the solution where PE, PP, and PS are recovered using seven machines is recommended in terms of GOP robustness. Moreover, validation using the observed sales prices of plastics between 2012 and 2014 according to resin type shows that the recommended solution leads to moderate profitability of the sorting facility throughout the above-mentioned period.

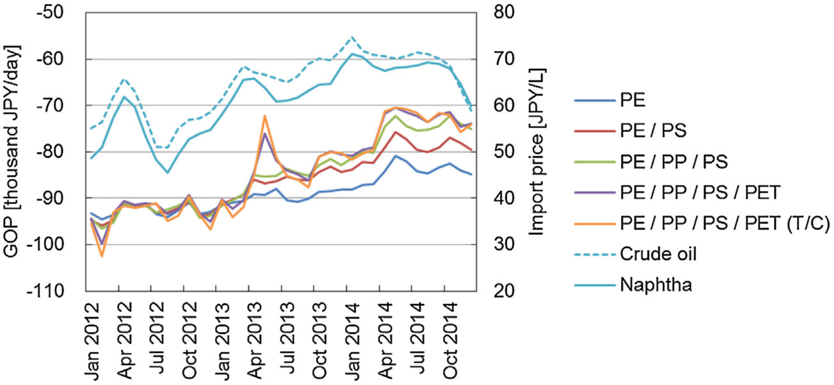

Fig. 8. The GOPs for the five dominant solutions and the import prices of crude oil and naphtha between 2012 and 2014.

Conversely, an optimal solution that is the most profitable under a specific condition (e.g., recovery of PE, PP, PS, and PET for a relatively high naphtha import price) loses its edge because of a decline in the naphtha import price. In this context, profit variability analysis for different solutions is considered to be particularly useful for avoiding selection of such a risky solution.

In addition, the sorting facility might also be expected to enhance the flexibility of a recycling system for variable external factors, because resin types targeted for sorting can arbitrarily be selected by changing the settings of the automated sorting machines. However, the number of installed machines is different in each of the five solutions, which means that additional machines should be installed or surplus machines should be stopped depending on the sales prices of recovered plastics to retain the optimized condition. In other words, even though the sorting machines are functionally flexible in selection of resin types targeted for sorting, such an advantage does not necessarily have a role in maximizing the profit of a sorting facility under fluctuations in plastics sales prices. For example, once a facility installs seven sorting machines for recovering three resin types, there is a feeble chance of selecting a combination of three resin types other than that of PE, PP, and PS, as shown in Fig. 5. This is because relative values among different resin types will rarely be reversed owing to the strong correlation between the sales prices of different resin types mediated by the import price of naphtha.

In addition to the sales prices of plastics, other parameters relevant to the profit of a plastic sorting facility, such as the quantity of waste plastics and the price of electricity price, are externally determined. The resin composition of waste plastics (see Table 3) is also variable, and its change may affect profitability. For example, an increase in the collected amount of a resin type that can be sold at a relatively high price (e.g., PP) will have a positive effect on profitability, whereas an increase in the amount of PVC/D will incur a larger disposal cost. Therefore, for a more comprehensive analysis of the potential solutions, the variability of the resin composition of waste plastics and the relationships between different resin types need to be analyzed. However, contrary to the plastics sales prices, consistent time-series data are not available for the resin composition of waste plastics in Japan presently. Such a data limitation could be a practical issue for the framework developed in this study.

The advantage of the developed framework over the conventional Monte Carlo simulation-based optimization lies in narrowing down the potential solutions to the practically meaningful ones. This could be accomplished by eliminating unrealistic combinations of parameter values (e.g., the price of different resin types) via analysis of their correlations with the determinant factor (e.g., the oil or naphtha import price). This advantage will be beneficial to decision-making for recycling of other waste products from which different types of materials can be recovered. Here, the identification of a valid determinant factor and relational analysis among variable external parameters will be a key factor for the effective application of the proposed framework.

5. Conclusions

In this study, we developed a framework for the variability-based optimal design of a plastic sorting facility for constructing a robust recycling system over external changes in the market. Optimization of the sorting processes for maximizing the profitability measured by the GOP and variability analysis considering changes in the import price of naphtha were performed by combining IP and Monte Carlo simulation. Distributions of the potential optimal solutions and variability of the profit were visualized according to the import price of naphtha. Based on the results (under the assumption that external factors except the prices of naphtha and plastics are constant), we recommended the solution where PE, PP, and PS were recovered since the solution was considered to be the most robust in terms of stability of the GOP. The solution was validated with the observed sales prices of plastics. Consequently, the recommendation was shown to be robust over the variability of sales prices of plastics. This result indicates that the developed framework is useful for designing a plastic sorting facility in consideration of robustness over changes in the plastics sales prices.

Several issues regarding the framework developed through the present study persist. First, it should be noted that the results derived using Monte Carlo simulations generally depend on the validity of the probability distributions assumed for the respective variables. Here, we assumed that variations in plastics sales prices that were not explained by the fluctuation of the naphtha import price were normally distributed, and the distributions of the sales prices in Japan were estimated on the basis of the statistics for the interval between 2007 and 2011. In order to apply this framework to different periods, different countries, or different kinds of waste to be recycled, the probability distributions of the relevant external parameters need to be examined accordingly.

In addition, the results obtained from the proposed framework do not necessarily provide decision-makers with explicit criteria for selecting a single solution, whereas optimal solutions can be narrowed down to a small number of dominant solutions. Decision-makers need to select one of the dominant solutions under market uncertainty factors, such as changes in the oil price. In this study, the multiple variable parameters (the sales prices of the different resin types) were associated with a common determinant factor (the import price of naphtha) and we identified five dominant solutions. However, the naphtha import price still controls which solutions may be considered advantageous and which may not. Consequently, future research should focus on improving the developed framework by incorporating a probabilistic outlook for the oil price.

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