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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

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.

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.

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,