Resources, Conservation & Recycling 131 (2018) 192–205

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Performance evaluation of material separation in a material recovery facility using a network flow model

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ARTICLE INFO

Keywords:
Material separation
Recycling
Network flow model
Model parameter estimation

ABSTRACT

In this paper, we model the recycling process for solid waste as performed in a material recovery facility. The intent is to inform the design and evaluation of a material recovery facility (MRF) in order to increase its profit, efficiency and recovery rate. We model the MRF as a multi-stage material separation process and develop a network flow model that evaluates the performance of the MRF through a system of linear equations. We estimate the parameters of the network flow model from historical data to find the best fit. We validate the model using a case-study of a light-packaging recovery section of an MRF in Spain. Additionally, we examine how uncertainty in the input material composition propagates through the system, and conduct a sensitivity analysis on the model parameters.

1. Introduction

Recycling is a major element of integrated solid waste management (SWM) in developed countries. Recycling of solid waste is a preferred option relative to landfill and incineration, due to the rapid depletion of landfill space and air pollution emissions from incineration (Chang and Pires, 2015). Furthermore, recycling permits the recovery of valuable raw materials. Consequently, many countries have enacted national and regional waste legislation that require recycling, such as the Resource Conservation and Recovery Act which implements the Sustainable Materials Management Program in the United States (Chang and Pires, 2015). In Spain, the Waste Framework Directive sets a target for Spain to recycle 50% of its municipal solid waste by 2020 (Milios and Reichel, 2013). A recycling program can differ in its collection method (single, dual or multi-stream). In this research we consider the collected municipal waste, which is processed at a material recovery facility (MRF). The MRF is a system of mechanical and manual separation processes that sorts the multi-stream waste to recover recyclable materials. MRFs in the US and Spain are facing challenges due to volatile scrap market prices (e.g. for plastic waste (Ragaert et al., 2017)) as well as changing scrap buyer requirements. The latter challenge stems from China's Operation Green Fence. Since 2013, China, a major importer of recyclable waste, turns away recyclable materials that fail to meet stricter contaminant levels (Gu et al., 2017). Another challenge is the variability in the composition of the waste streams received by the MRFs. To address these challenges, it is crucial that MRFs understand how their operating performance depends on the scrap-market prices and quality requirements, as well as on the waste input streams. This understanding can allow the MRFs to examine adaptation strategies in light of the scrap market dynamics and input variability. In this paper we develop and test a network flow model for an MRF. The intent of the model is to provide a tool for predicting the performance of an MRF, and for showing how this performance depends on the configuration and parameters of the system, and on the input materials. Potential applications include cost-benefit analyses of modifications to the design and operation of an MRF; for instance, these modifications might increase the recovery or grade of a profitable material.

The material recovery model developed in this paper will contribute to furthering the development of a circular economy. The model allows for the determination of the material recovery rate and grade from a municipal waste input stream, and can be used to identify system improvements that both increase the quantity and/or quality of the valuable recovered materials, as well as reduce the amount lost to landfills. Whereas this model has been developed for a municipal waste application, it should also apply to other material recovery systems that use similar separation technologies. For instance, we expect that the model, with some adaptation, can be applied to the separation step in the recovery system for end-of-life vehicles, which comes after the dismantling and shredding steps.

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https://doi.org/10.1016/j.resconrec.2017.11.021
Received 29 December 2016; Received in revised form 23 November 2017; Accepted 25 November 2017

1.1. Literature review

Solid waste recycling is part of the larger framework of waste management, which examines the flow of waste from generation in rural or urban settings to treatment, recovery or disposal. There is an extensive literature on waste management. In particular, we cite the research that focuses on decision-making processes, namely capacity-planning of facilities for treatment and material recovery, routing systems for waste collection, and resource allocation (Antmann et al., 2013; Chang et al., 2005; Huang et al., 2005; Shi et al., 2014). Additionally, we mention the research that includes environmental considerations. For plastic waste management, Rigamonti et al. (2014) look at different collection-routing strategies from an energy recovery perspective, while Shonfield (2008) carries out a life cycle assessment (LCA) study of a range of plastic recycling technologies. Gaustad et al. (2012) examine the environmental and economic impact of various technologies used for aluminum recycling. Kirkeby et al. (2006) examine the LCA of material flows using EASEWASTE, a computational model tool developed for this purpose. Several papers rely on estimated parameters to characterize the performance of an MRF for a particular material flow: Kirkeby et al. (2006) introduce mass transfer coefficients, parameters input by the user to characterize a material's overall recovery; Palmer (1999) and Diaz et al. (1982) use recovery factor transfer function for each material flow in each unit in an MRF.

Material separation of collected waste is carried out mechanically in MRFs based on the physical properties of each material. For instance, aluminum materials are sorted by virtue of their electrical conductivity using eddy-current separation equipment (Braam et al., 1988; Schloemann, 1982). Ferrous materials are sorted by magnet separators in pulley, drum or belt form (UNEP, 2005). Glass and plastic (including HDPE, PET and Tetrabrik) are separated from other materials by detect-and-route systems, whereby sensors detect target materials and air jets divert the localized objects (Stressel, 2012). Sensors using spectroscopic near-infrared (NIR) imaging have been shown to successfully sort between different types of plastics after training with statistical pattern recognition techniques (Van Den Broek et al., 1997). Huang investigated the use of optical sensors for multi-feature recognition of different waste mixtures (Huang et al., 2010). MRFs also carry out separation based on particle properties at the start of the system configuration: screening, usually done with trommels, separates based on object size (Stressel, 2012; UNEP, 2005); ballistic separators distinguish between flat, light items (e.g., paper, films) and heavy, rigid items (e.g., containers) based on particle elasticity and aerodynamic properties (Hershaft, 1972; Testa, 2015). In addition to automated sorting technologies as described above, manual sorting is also used in some MRFs. For instance, personnel in sorting stations situated before the trommels collect large-size objects while those in stations before the final baling of the plastics and aluminum output streams remove non-valuable waste (Stressel, 2012; UNEP, 2005).

MRFs sort materials using a sequence of separation processes. Beyond an understanding of the physical process for each separation unit, we need to model all the units as a connected network. Modeling of a network of material separation processes has been carried out in other fields, most specifically in mineral processing (Mckeon and Luttrel, 2012; Noble and Luttrell, 2014a,b). These papers use a linear circuit analysis approach, with the separation function defined for different separation technologies based on physical properties. In (Dahmus and Gutowski, 2007; Gutowski et al., 2008, 2007), a similar approach, called 'Bayesian separation', is introduced to define material separation models from a probabilistic point of view. The probabilities for correct routing of target material and non-target material are also defined. Vanegas et al. (2015) use this approach to model the recycling of LCD TVs.

Several papers have studied the costs and operations of an MRF in various contexts: Metin et al. estimated the investment and operating costs of different municipal MRFs in Turkey using city-wide aggregate data (Metin et al., 2003); Kang and Schoenung examined the cost drivers of an existing e-waste MRF (Kang and Schoenung, 2006); Li et al. considered how sorting strategies can impact the utilization of scrap in a secondary aluminum production process. (Li et al., 2011). However, these papers do not model the material flows through the individual separation units, but rather assume a given material recovery rate. There is limited literature concerning the actual design optimization of the network of separation processes used in MRFs. Wolf (Wolf, 2011; Wolf et al., 2013), and Testa (Testa, 2015) provide the groundwork for the development of a network flow model which can represent an MRF with multiple output units and recirculating streams. In this paper, we formulate a network flow model for an MRF as done in these prior works, provide an approach for parameter estimation and present a case study illustrating the model.

2. Mathematical model

The aim of the mathematical model is to represent the material separation processes in terms of the mass flow of material in a network of sorting units that includes recirculation loops. We assume a stationary flow of input material, and no build-up or buffering of any of the flows in the MRF.

We model each separation process on a per material basis, with an empirically-derived separation (or efficiency) parameter which quantifies the fraction of a material sent to each output stream of a sorting unit. We do not attempt a physical modeling of the sorting units; such models are rarely available for a whole MRF network (Chang and Pires, 2015). Future work could incorporate the physical parameters of the sorting unit that determine its separation efficiency (e.g. height of the magnet, strength of the current) by making the separation efficiency a function of these physical parameters.

As the building block for the network model, we consider a multi-output sorting unit that sorts a mixture of M materials into K output streams. For each material m, we define a mass flow rate of f_i^m in the input stream (e.g., ton per hour) to unit i. The sorting unit will separate this material input into K output streams. The mass flow in the output stream k is$q_{i,k}^m f_i^m$, where $q_{i,k}^m$is the fraction of the input stream of material m that is sorted into output stream k by unit i.$q_{i,k}^m$ is called the separation parameter. Consequently we have $\sum_{k=1}^{K} q_{i,k}^m = 1$. Fig. 1 shows the most common case when there are only $K = 2$ output streams: if unit i sorts for target material type ($m = \mathrm{T}$), it diverts a fraction of its flow, denoted by $q_{i,j}^{\mathrm{T}}$, to target unit j, and diverts $q_{i,k}^{N}$of the flow of non-target material type(s) ($m = \mathrm{N}$) to non-target unit k. $q_{i,j}^{\mathrm{T}}$and $q_{i,k}^{\mathrm{N}}$are expected to be greater than 0.5.

We use this building block to develop the mathematical model for an MRF. An MRF can be represented as a network of multi-output units, as shown in Fig. 2. We model the system configuration with three types of units: a set I of input nodes, a set S of sorting units and a set Z of output nodes. Each input node feeds an input stream to an initial sorting unit. The input to each sorting unit can consist of an input stream from an input node, plus the output streams from other sorting

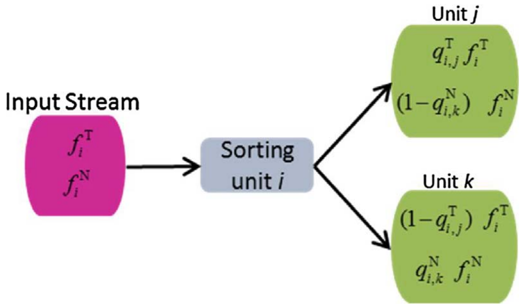

Fig. 1. Scheme of a multi-output unit sorting an input mixture of target and non-target materials into 2 streams.