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Material flow cost accounting (MFCA)–based approach for prioritisation of waste recovery

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ABSTRACT

Waste recovery has become one of the most important strategies to reduce environmental issues and improve economic performance in industry. Thus, different systematic approaches have been developed for waste recovery. However, most of the developed waste recovery approaches do not account for the hidden cost incurred from various processing steps as a criterion for prioritisation of waste recovery. This aspect can be determined by the concept of material flow cost accounting (MFCA). Hence, in this work, a novel MFCA-based approach is developed for prioritisation of waste recovery with consideration of hidden costs embedded in process streams. Two case studies are solved to illustrate the developed approach. It can be seen that hidden unit cost (HUC), carry-forward cost (CFC), amount and quality of discharged waste are important factors that significantly affect the prioritisation results. The developed approach then balances the trade-off among these factors to determine the minimum total hidden cost (THC) of discharged waste, and thus improve the economic and environmental performances of an industrial process.

1. Introduction

Waste recovery is one of the important strategies to achieve environment-friendly production while also enhancing economic performance. To promote in-plant waste recovery, numerous research works have been conducted for waste recovery in different industries in past decades. For instance, orange waste from beverage industry (Rezzadori et al., 2012), biodegradable wastes from grain industry (Kliopova et al., 2013), aluminium scrap from aluminium manufacturing process (David and Kopac, 2013), waste heat from steel industry (Zhang et al., 2013), cork wastes from cork industry (Nunes et al., 2013), etc. Note that the wastes are recovered from the manufacturing processes and converted into value-added products (e.g., animal feed, bio-oil, charcoal, pectin, ethanol, adsorbent, renewable fuel, etc.) to reduce environmental impacts and increase economic performance of manufacturing process.

On the other hand, different systematic approaches to reduce waste generation and raw materials consumption have also been developed. Examples include insight-based pinch analysis (El-Halwagi et al., 2003; Manan et al., 2004; Prakash and Shenoy, 2005) and mathematical programming approaches (Bagajewicz and Savelski, 2001; Karuppiah and Grossmann, 2008; Lee and Grossmann, 2003; Tan and Cruz, 2004) developed for the synthesis of material recovery networks. Such networks are also known as resource conservation networks (RCN). The material recovery networks include mass-exchange network (MEN) (El-Halwagi and Manousiothakis, 1989), reactive mass-exchange networks (REAMEN) (El-Halwagi and Srinivas, 1992), combined heat and reactive mass exchange network (CHARMEN) (Srinivas and El-Halwagi, 1994), water recovery network with reuse/recycle (Wang and Smith, 1994; El-Halwagi et al., 2003; Manan et al., 2004; Prakash and Shenoy, 2005), water network with regeneration (Kuo and Smith, 1997; Ng et al., 2007a, 2009a), total water network (Kuo

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and Smith, 1998; Ng et al., 2007b, 2009b), and property-based material recovery network (Kazantzi and El-Halwagi, 2005). Note that the abovementioned RCNs can be synthesised via insight based approaches, which also known as pinch analysis; for example, limiting composite curve (Wang and Smith, 1994), material recovery pinch diagram (El-Halwagi et al., 2003; Prakash and Shenoy, 2005), source composite curve (Bandyopadhyay and Ghanekar, 2006), water cascade analysis (Manan et al., 2004), value composite curve (Towler et al., 1996), hydrogen surplus diagrams (Alves and Towler, 2002; Zhao et al., 2006), etc. Besides, various mathematical optimisation approaches were also presented to synthesise RCNs. For instance, early works in mathematical optimisation approaches were presented by Takama et al. (1980a; 1980b; 1981) for water network synthesis; deterministic optimisation approaches such as Symmetric Fuzzy Linear Programming (Tan and Cruz, 2004), Mixed Integer Nonlinear Programming (Karuppiah and Grossmann, 2008), Nonlinear Programming (Yang et al., 2000), etc., were presented for synthesis of robust water reuse networks, integrated water network, and wastewater reuse network, respectively. Meanwhile, stochastic optimisation approaches, which using generic algorithm, were used for network design (Tsai and Chang, 2001), network analysis (Shafiei et al., 2004), etc. The various network synthesis approaches have been reviewed by Bagajewicz (2000) and Foo (2009). Viewing the benefits of insight-based approaches and mathematical optimisation approaches, hybrid approach (Automated Targeting Method, ATM) was first proposed by El-Halwagi and Manousiouthakis (1990) for the synthesis of mass exchange network and then further extended to RCNs by Ng et al. (2009a) as well as property based RCNs (Ng et al., 2009c). Note that although many approaches have been presented in previous works for targeting and design of RCNs, the developed approaches are mainly focusing on minimising waste discharge and fresh resources consumption via maximising material recovery as well as minimising operating and annualised costs. Note also that the recovery strategy is mainly based on the quantity and quality of the waste streams. In case where the quality of the waste streams is same, the previous proposed approaches are not able to prioritise the streams for recovery.

In order to address the limitation of the previous approaches, several prioritisation approaches were developed for waste recovery. For instance, the waste stream prioritisation matrix ranks alternatives based on various criteria (i.e. health and safety risk, material value, existing and potential market, job creation, litter abatement, etc.) (NWMSI, 2005) was developed. Besides, Wang and Gaustad (2012) developed a weighted sum model based on economic value, energy saving potential, and eco-toxicity. Although multiple criteria are considered in these previous prioritisation approaches, neither approach accounts for the hidden cost of waste streams. Such hidden costs are another important criteria for waste recovery since they reflect the wasted inputs that are embedded in waste streams. The hidden costs can be determined based on the concept of Material Flow Cost Accounting (MFCA) (Kokubu et al., 2009), and can thus potentially be taken into consideration in an improved prioritisation approach for waste recovery. Therefore, in this work, a novel MFCA-based approach is introduced for prioritisation of waste recovery based on the hidden cost. This proposed approach can enable improved decision-making for industrial waste recovery purposes.

MFCA is a tool of Environmental Management Accounting (EMA) (Fakoya and Van Der Poll, 2013) that focuses on imputing cost shares to waste streams (Kokubu et al., 2009). The ultimate purpose of MFCA is to mitigate environmental issues and concurrently improve economic performance (Onishi et al., 2008). This concept has been successfully used in numerous industrial applications, such as lens manufacturing (Anjo, 2003; Schmidt and Nakajima, 2013); chemical, healthcare and pharmaceutical production (Kokubu et al., 2009); electronics manufacturing (kokubu and Tachikawa, 2013); optoelectronic and electric power industry (Trappey et al., 2013); automotive industry (Kokubu et al., 2009); ceramic tiles production (Hyršlová et al., 2011); heavy machinery production (Tang and Takakuwa, 2012); and the brewery industry (Fakoya and Van Der Poll, 2013). These cases demonstrate that MFCA helps in improving overall economic performance of companies.

MFCA traces input and output material flows in both physical and monetary units so that the information of waste cost can be captured precisely (Jasch, 2009). In MFCA, waste is treated as a by-product. The main consequence of this assumption is that the manufacturing cost is not only used to produce the desired products, but also the undesired by-products (wastes). The latter is thus said to bear part of the processing cost of all upstream processing steps. According to Strobel and Redmann (2002), there are four types of costs (i.e. material, system, energy and waste management costs) taken into consideration under the concept of MFCA. These costs are distributed to wastes and products as shown in Fig. 1 (Kokubu and Tachikawa, 2013). The distribution is based on the attribution of specific activities to the generation of product and waste streams.

As shown in Fig. 1, the material, system and energy costs are attributed to product and waste according to the material distribution percentages (70% of product and 30% of waste). On the other hand, all the waste management costs are 100% attributed to waste (Kokubu and Tachikawa, 2013). Since the wastes possess significant cost that is overlooked by conventional cost accounting practices, the cost allocated to wastes is known as a hidden cost. In order to reduce this cost and hence improve economic performance, waste recovery is a vital strategy to implement in manufacturing companies. In addition, following the concept of MFCA, each individual waste stream has an associated hidden cost which reflects the cumulative effort invested through successive processing steps to generate these streams. This concept makes the hidden cost an important criterion for waste stream prioritisation. However, as mentioned previously, this hidden cost is overlooked in conventional accounting prioritisation approaches. Hence, a novel prioritisation approach that incorporates the concept of MFCA is developed in this work.

The rest of this paper is organised as follows. A formal problem statement is given, which is followed by a mass balance and cost computation formulation of MFCA-based approach. Next, two case studies, an aluminium production system (single-waste generation process) and a sago starch extraction process (multi-waste generation process) are solved to illustrate the proposed approach and the obtained results is analysed. Finally, conclusions and prospects for future work are given at the end of the paper.

2. Problem statement

The problem definition for the prioritisation of waste recovery in manufacturing process is stated as follows: Given a number of processes $i \in I$ in a specific boundary system generate intermediates $k \in K$, products $p \in P$ and wastes $w \in W$ as shown in Fig. 2. In order to prioritise the waste streams for recovery, a novel MFCA-based approach is introduced in this work. The hidden cost of process i ($Cost_i^{HC}$) can be determined by quantifying the wastes in process i in monetary units. The objective is to determine the target or benchmark for the minimum total hidden cost of discharged waste ($Cost^{THC,Y}$) of the specific boundary system.