Available online at www.sciencedirect.com
ScienceDirect
European Journal of Operational Research 186 (2008) 953–964
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH
www.elsevier.com/locate/ejor

Discrete Optimization

Fuzzy chance constrained linear programming model for optimizing the scrap charge in steel production

Aiying Rong [a,*,1], Risto Lahdelma [b]

[a] Technical University of Denmark, Department of Manufacturing Engineering and Management, Building 425, 2800 Kgs, Lyngby (Copenhagen), Denmark
[b] University of Turku, Department of Information Technology, Joukahaisenkatu 3-5, FIN-20520 Turku, Finland

Received 10 February 2006; accepted 1 February 2007
Available online 20 March 2007

Abstract

Optimizing the charge in secondary steel production is challenging because the chemical composition of the scrap is highly uncertain. The uncertainty can cause a considerable risk of the scrap mix failing to satisfy the composition requirements for the final product. In this paper, we represent the uncertainty based on fuzzy set theory and constrain the failure risk based on a possibility measure. Consequently, the scrap charge optimization problem is modeled as a fuzzy chance constrained linear programming problem. Since the constraints of the model mainly address the specification of the product, the crisp equivalent of the fuzzy constraints should be less relaxed than that purely based on the concept of soft constraints. Based on the application context we adopt a strengthened version of soft constraints to interpret fuzzy constraints and form a crisp model with consistent and compact constraints for solution. Simulation results based on realistic data show that the failure risk can be managed by proper combination of aspiration levels and confidence factors for defining fuzzy numbers. There is a tradeoff between failure risk and material cost. The presented approach applies also for other scrap-based production processes.

Keywords: Fuzzy sets; Linear programming; Chance constraint; Scrap charge optimization; Steel production

1. Introduction

A general trend during the past decades is that scrap-based steelmaking has increased its share, reaching around 40% of global crude steel production in 2001 (Rautaruukki, 2001). Steel is also the world's most important recycled material. Use of the steel scrap as a raw material for steelmaking results in saving 600 million tonnes of iron ore and 200 million tonnes of coke each year (EUROFER, 2001). With the growing concern on environmental issues, the popularity of using scrap could further increase because scrap-based steelmaking emits significantly less CO_2 as compared with integrated steelmaking using metallurgical coke as reductant for iron-making. Undoubtedly, the use of the scrap offers the opportunity to produce high quality products most economically.

* Corresponding author. Tel.: +45 45254768; fax: +45 45256005.
E-mail addresses: aiying.rong@gmail.com, ar@ipl.dtu.dk (A. Rong).
[1] The research was done when the first author was employed by Universtity of Turku.

0377-2217/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ejor.2007.02.017

There are two challenges in scrap charge optimization:

- The constituents in scrap and steel products are diverse. With the development of steel products of higher grades and performance, use of steel materials in combination with nonferrous metals or non-metallic materials has increased. Depending on the melting process and the requirements for the particular product, some of the constituents in scrap are considered impurities while others are valuable additives. Therefore, it is essential that a mix of proper kinds of scraps in right proportions is selected for each product.
- The diverse scrap materials are generally sorted into different classes but the materials included in a class can be very heterogeneous. This means that there are large deviations in material properties inside a class, sometimes larger than between classes. Therefore, it is difficult to come up with accurate chemical composition analyses (element concentration) for each kind of scrap, and this uncertainty is propagated to the scrap mix.

The scrap-based steelmaking process starts by charging the predetermined scrap mix into an electric arc furnace (EAF). Melting a single charge in the furnace is called a *heat*. When the charge is melted, the uncertainty in the chemical composition of the scrap causes a considerable risk for the outcome failing to satisfy the composition requirements. The objective in scrap charge optimization is to select the most economical scrap mix for each produced steel grade while minimizing the failure risk caused by uncertainties in raw material consistence.

There are three kinds of charge optimization models based on the length of the planning horizon: the single-heat model (AFS, 1986) for short-term planning (e.g. daily operations), the multi-heat model (Kim and Lewis, 1987) for medium-term planning (e.g. weekly or monthly) and the product recipe model (Lahdelma et al., 1999) for long-term planning (yearly). Any charge plan is implemented on single-heat basis and on-line analysis is applied to identify whether the outcome matches the predicted characteristics and to correct the possible bias in future predictions (Wilson et al., 2001). However, if charging is planned using the single-heat model, this may result in non-optimal use of raw materials. Minimizing raw material costs in one heat can eat up the cost-efficient raw materials and therefore increase the costs in future heats. The multi-heat model can allocate the available raw materials optimally among the different heats based on the current raw material stock and predicted deliveries. For long-term planning, it is more convenient to use the product recipe model which can be viewed as a model where all heats of the same product are grouped. Therefore, the product recipe model can be much smaller than the multi-heat model. The long-term scrap charge plan is designed based on forecast customer orders and possible available raw materials. The product recipe model can also be applicable to medium-term planning.

In terms of handling uncertainty, there are several methods of constraining failure risks. Bliss (1997) added safety margins to the product standard by using a tighter product standard in optimization. Lahdelma et al. (1999) added safety margins to the chemical composition for scrap in optimization. Adding safety margins can be viewed as an extension of the deterministic model to accommodate the uncertainty. Turunen (2000) constrained the failure risk based on stochastic chance constraints to guarantee that the failure rate is less than a predetermined level (or to allow small violations in some constraints). However, in the stochastic chance constrained programming formulation, the stochastic parameters are generally assumed to follow the normal distribution. Based on this assumption, the chance constraints can be implemented elegantly as a non-linear deterministic model (Kall and Wallace, 1994; Watanabe and Ellis, 1994; Kürsad and Gökçen, 2007). Kürsad and Gökçen (2007) further approximated this non-linear model by a linear model. In our current problem, we represent concentration parameters by normal distributions where negative values are forced to be zero. When the standard deviation of the element concentrations is large in relation to the mean, the resulting distribution will be skewed. When the stochastic parameters do not follow the normal distribution, some further assumptions are needed to transform stochastic chance constraints into their deterministic equivalent. The problem can be even more difficult if the stochastic model includes simultaneously chance constraints and ordinary constraints with stochastic parameters, because handling ordinary stochastic constraints is also complicated (Kall and Wallace, 1994). In such situations it is easier to handle uncertainties using fuzzy set theory (possibility theory, Zadeh, 1978).

In this paper, we formulate the scrap charge optimization problem based on the product recipe