1. Introduction

Flat glass manufacturing is a continuous process whereby a ribbon of molten glass is produced in a furnace and then cooled on a bath of molten tin to ensure flatness. The continuous glass ribbon is then carried on rollers through an annealing lehr, a bath of molten tin to ensure flatness. The continuous nature of the process causes some glass to be wasted if it is cut and cannot be picked up in time. Such wasted glass is called cycle time scrap. Even if any glass cut could easily be offloaded, the laying out of the customers’ orders on to the ribbon can incur waste known as layout scrap. We define and model a problem of optimizing the cutting sequence and the layout of the glass being cut so that the total amount lost to cycle time scrap and layout scrap is small. We develop heuristic solution methods using construction and local search algorithms for this problem. We validate the proposed approach using real data from a major float glass manufacturer and show that it produces manufacturing yields greater than 99%.
be cut within a certain time interval. Their sequencing issue is different from that of our float glass problem, where sequencing is caused by the relation between the cutting and offloading operations.

Another related problem is two-stage hybrid flow shop (HFS) scheduling with no intermediate storage and identical parallel machines in the second stage. The cutting and offloading operations in the float glass problem make up the two stages of a flow shop, and minimizing cycle time scrap is equivalent to scheduling to minimize processing time. Srikantharajah (1993) studies worst case performance analysis for no-wait (or blocking) flowshops with parallel machines. However, HFS scheduling does not address layout scrap. Moreover, the operational restriction such as machine dedication, which will be explained in the next section, makes the float glass problem harder. See Linn and Zhang (1999) for general HFS scheduling, and see Gupta and Tunc (1991) for the HFS with parallel machines at the second stage. Also, see Pinedo (2008) for the flow shop with limited intermediate storage.

Other related literature concerns cyclic scheduling. When a set of orders is produced in a no-wait flowshop and each order has multiple units, the same schedule is repeated over and over again. This repeated pattern is called a cyclic schedule in operations research (see McCormick et al., 1989 or Pinedo, 2008) and a campaign in chemical processes (see Birewar and Grossmann, 1989a,b). The float glass problem also yields cyclic schedules, but because of the machine dedication and machine cycle time properties, which will be explained in the next section, the type of cycles that appear in the float glass problem has a different structure than those considered previously.

With regard to real-world applications of flat glass cutting, Arbib and Fabrizio (2007) proposed a heuristic algorithm to minimize trim loss in float glass manufacturing for the automotive market. The cutting phase is the same as our's in that vertical and horizontal cutting is made. However, after cutting, glass is stacked in a buffer and the unloading process is very different than our's. In our float glass problem, unloading (offloading) occurs directly on a conveyor line rather than a separate buffer. Therefore, offloading and cutting should be simultaneously considered. Another real-world glass cutting problem studied by Puchinger et al. (2004) considers an additional cutting constraint that customer orders are grouped according to the destination of delivery. Dash et al. (2007) study the problem of producing rectangular plates for a steel company to minimize scrap, but do not consider the sequencing issue. Thus, none of these earlier works adequately captures the full complexity of the float glass problem.

Na et al. (to appear) introduce FGSP (float glass scheduling problem) in which cycle time scrap is considered but layout scrap is not. They show that the problem is NP-hard, and identify when each of the problem's components are polynomially solvable and when they induce hardness. In addition, they propose a simple heuristic algorithm, provide its worst-case performance bounds, and demonstrate that the bounds are tight. When the number of machines is two, the worst-case performance is 5/3.

Na (2011) shows that the float glass problem is NP-hard in general, and introduces a mixed-integer programming (MIP) formulation. However, because of the MIP's size and difficulty, state-of-the-art commercial solvers are unable to find good solutions within a reasonable amount of time. Therefore, we present a heuristic solution approach to solve the float glass problem. We will empirically show that the proposed heuristic solution approach produces nearly optimal solutions for a collection of randomly generated and real-world test problems.

In the Problem Description section, we introduce the relevant characteristics of a float line, and describe the sequencing and layout optimization problem. In the Solution Approach section, we present heuristic algorithms to solve the problem. The performance of the proposed algorithms is demonstrated in the Computational Results section. We conduct sensitivity analysis on the number of offloading machines in the Sensitivity Analysis section.

2. Problem description

2.1. Basic terminology

Our problem concerns processing a given set of customer orders (usually about 60) over a 24 h working shift. Each customer order consists of a specified number of identical pieces of glass (plates) of specified dimension (length × width × thickness). For example, a customer might order 200 plates of dimension 20” × 40” × 1/8”.

Plates are created by a two-step cutting process in which the ribbon of glass is first scored (etched where plates will be divided), and then snapped along the scores. The x-cuts stretch across the width of the ribbon perpendicular to its direction of flow, and the y-cuts are at right angles to the x-cuts and stretch between two consecutive x-cuts.

The glass between two consecutive x-cuts is called a snap, and the snap time is the time between the two x-cuts. Because glass of a given thickness and width is produced at a constant rate, snap time is proportional to the length of glass between the two x-cuts. Between two consecutive x-cuts, the y-cuts divide a snap into two or more plates. Fig. 2 illustrates the terminology of a float glass line. Layout scrap and cycle time scrap are also shown in the figure. Recall that layout scrap is caused by not using the ribbon width optimally when laying out the plates, and cycle time scrap is caused by improper sequencing of snaps on the ribbon.

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