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A Dynamic Programming Algorithm for the Online Cutting Problem with Defects and Quality Grades

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Abstract: In this article, we propose a dynamic programming based algorithm for an online glass cutting problem that arises in the glass industry. In flat glass production, a continuous ribbon of flat glass is cut into glass products of various sizes as it flows on a conveyor belt. The glass ribbon contains defects of different types based on their severity and each glass product belongs to a quality class that indicates the maximum number of defects of each type that can be tolerated. Since the location and type of defects are detected in real time using a camera, the cutting problem has to be solved online and each cutting decision is made within a few seconds. The primary goal of this cutting problem is to minimize the amount of leftover (*scrap*) glass resulting from the cut products. The proposed algorithm uses a look-ahead strategy to solve a static cutting problem at each iteration to determine the products to be cut within a fixed horizon length, but implements only the first one or few of these cuts per iteration. We evaluated the algorithm on a set of realistic problems reflecting the parameters of current flat glass production lines. Computational results indicate that the proposed algorithm can reduce the amount of scrap glass by an average of 26.1%.

Keywords: cutting stock problems, dynamic programming, flat glass production, defects, online algorithm.

1. INTRODUCTION

In this article, we present an online algorithm for a cutting problem that arises in flat glass production. In a flat glass production line, which is also called a *float* line, molten glass from the furnace is formed into a ribbon that cools down and solidifies as it moves on the conveyor belt. Rectangular glass products of various sizes are then cut from this flat glass ribbon while the conveyor is moving at a constant speed. During the production process, defects of varying severity levels form on the glass ribbon. On the other hand, each glass product to be cut from the glass ribbon belongs to a quality class that specifies the maximum number of defects of each type that are permitted on the product. A product that is cut from a piece of glass that does not meet the requirements of its quality class has to be discarded as scrap. Scrap glass is sent back to the furnace to be melted and recycled, which results in increased production costs as well as reduced productivity. Thus, the primary goal of the cutting process is to minimize the amount of scrap glass resulting from the cuts. Maximization of the total value obtained from cut products is also taken into consideration in this process. The camera that identifies the coordinates and type of the defects is located only 3-4 seconds before the cutting bridges that score the cuts on the ribbon. Therefore, the time to make the cutting decisions is quite limited. Also, at the time of decision making, the length of the glass ribbon with defect data usually does not exceed 12-15 meters. Therefore, cutting decisions need to be made with limited data and within a very short timeframe. In this work, we propose an online dynamic programming based algorithm to determine the type and location of the products to be cut from the glass ribbon in real time. The algorithm solves a series of static cutting problems over partially overlapping lengths of glass ribbon.

In the literature, the two dimensional glass cutting problem described here is classified as a two-stage problem since the cuts are scored on the glass ribbon in at most two stages: an x-cut that cuts along the width of the glass ribbon end-to-end, (possibly) followed by a y-cut along the length of the ribbon that cuts the rectangle formed by the x-cut into smaller rectangles. The cuts are scored by bridges located over the glass ribbon. x-bridges use one cutting wheel to score the glass ribbon end-to-end while the y-bridges have cutting wheels at up to 3-5 positions along the y-bridge to enable simultaneous application of multiple y-cuts. The fixed number of cutting wheels on the y-bridges limits the number of product patterns or *configurations* that can be placed along the width of the ribbon. Usually the number of different configurations that can be cut on the float line does not exceed 10-15. We take advantage of this limited number configurations to reduce the two-dimensional problem over product types to a one dimensional problem over product configurations. An important feature of flat glass cutting process which separates it from many other cutting problems is that it allows strips of defective glass to be cut between configurations. These glass strips are recycled as scrap glass in an effort to avoid anticipated quality problems in later cuts. The industry standard is to perform such cuts immediately behind a serious defect, therefore they are known as Cut Behind Fault (CBF) cuts in float line terminology. Fig. 1 displays a glass ribbon on which a cutting pattern that includes three different configurations and one CBF is marked. The glass ribbon contains defects of two quality grades that are marked as small

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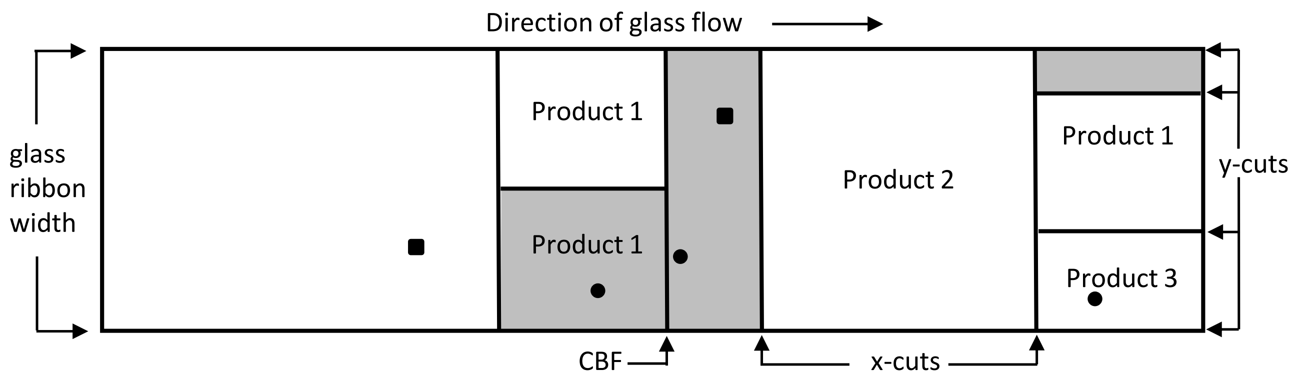

Fig. 1. Illustration of a cutting pattern placed on the glass ribbon on a float line

circles and squares. Three types of products (Products 1-3) that are cut using x- and y-cuts are marked with vertical and horizontal lines. Shaded areas represent the scrap glass that results from the placement. Products 1-3 are used to form three configurations consisting of one or two products each. The first of these configurations includes one Product 1 and one Product 3 as well as some scrap glass. Please note that this configuration can be cut using four cutting wheels on the y-bridge. The second configuration contains only one Product 2 followed by a CBF after the circle type defect. The last configuration consists of two units Product 1, one of which is discarded as scrap due to the circle type defect on it. Note that the same grade defect does not render Product 3 scrap since the two products belong to different quality grades: Product 3's quality grade allows a circle defect while Product 1's does not. One should also note that the last configuration requires another cutting wheel positioned in the middle of the glass ribbon. Therefore the three configurations displayed in Fig. 1 requires a total of five cutting wheels located at different positions on the y-bridge.

2. RELATED LITERATURE

Cutting problems have been studied extensively in the literature. One can refer to one of the various surveys available for an overview on the topic. (Dowsland and Dowsland (1992), Dyckhoff (1990), Bischoff and Wäscher (1995), Wäscher, et al. (2007)). Despite the large body of literature on cutting problems, studies on cutting problems with quality variations and defects is quite limited. One of first such studies that focus on quality variations is due to Gilmore and Gomory (1965). Here, the authors study the one and two dimensional versions of the static cutting stock problem where the value of the cut product depends on its position and propose a recursive algorithm to solve both versions. In a later study, Hahn (1968) defines a cutting stock problem with guillotine cuts and defects. In this problem, the products are not allowed to be placed on areas that contain defects. A dynamic programming method suggested in Gilmore and Gomory (1966) is used to solve this problem. Scheithauer and Terno (1988) also solve a more general version of the problem in Hahn (1968) where the cutting stock is not restricted to be a rectangle using dynamic programming. A more recent study by Gelder and Wagelmans (2009) focuses on a similar problem in the area of roller blind production and solves it using a two stage heuristic. Afsharian et al. (2014) also employ a dynamic programming based heuristic to solve a two dimensional cutting problem with defective areas that can be approximated by rectangular regions. There are also other studies on cutting problems where the cutting stock contains a single defect e.g. Carnieri et al. (1993), Neidlein et al. (2009).

There are several articles in the literature on one dimensional cutting problems where defects and/or quality grades are considered. For instance, Sculli (1981) defines a problem where small rolls of fixed size are cut from a long roll that contains defects. In this variant, size of the small rolls is a random variable due to the defects on the long roll. In another cutting problem from the timber industry, Faaland and Briggs (1984) define the process of cutting a tree into logs and cutting these logs further into lumber. In this problem, shape and quality variations on the tree require a specialized approach. In Sarker (1988), the cutting stock contains several punctual defects and the objective is to attain the maximum total value by cutting only through defects. In this variant, the value of each resulting piece depends on its length and the number of defects on it. Sweeney and Haessler (1990) discuss a one dimensional problem, in which the cutting stock contains various sections of hierarchical quality grades and customers also specify minimum acceptable quality grades for their orders. Aboudi and Barcia (1998) consider a variant taken from the paper industry. In this problem, a roll of paper containing a single defective area is cut vertically to produce a set of sheets. Since the sheets that contain a defective area are to be discarded, objective is to find a cutting plan that minimizes the total length of the defective sheets. In an application from the textile industry, Özdamar (2000) proposes a simulated annealing algorithm to create a cutting and wrapping solution where a cutting stock with multiple defects is first cut into smaller pieces and each piece is assigned a quality grade based on the defects it contains. Next, pieces with the same quality grade are wrapped to create rolls of given quality specifications. Although each of these problems bears similarities with the problem defined in this article, they all differ from the glass cutting problem in terms the way the defects, quality classes, and the conditions for creating feasible cuts. More importantly, all of the mentioned problems are static in nature, as opposed to the problem at