Customer Service vs Trim Waste in Corrugated Box Manufacture

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Many approaches to the problem of arranging customer orders for cutting or corrugation have focused on the minimization of trim waste. This views the corrugator more or less in isolation. When downstream machines or customer due-dates exist, however, customer service may suffer from the desire to keep scrap at a low level. Thus, if slightly higher levels of waste were accepted, the production scheduler might be able to improve performance regarding due dates.

We developed a simulation model for Domtar Packaging Ltd, of a corrugated cardboard box factory, which included the corrugation process and four finishing machines. Customer orders were generated via empirical and theoretical probability distributions, then sent through the model according to one of several scheduling rules. This allowed the relationship between various levels of trim waste and customer service to be viewed. Results of the simulation experiments, as well as a discussion of the model itself, are given. Comments and conclusions regarding both our model and corrugator algorithms in general are presented in the light of the role of the human scheduler in plants of this type.

Key words: cutting stock, due-dates, manufacturing, simulation

INTRODUCTION

Hundreds of research papers on the cutting-stock problem have collectively increased our professional knowledge and have led to numerous new formulations and improved solution procedures. While a few treatments have considered other objectives (e.g. long production runs) in addition to minimal trim waste, previous research generally has not considered the competitive nature of an industry in which major customers can request and receive priority service, including alterations to previously specified due-dates and order quantities. These dynamic aspects require flexibility in a firm's scheduling procedures that would likely lead to sub-optimal pattern layouts in a 'static' shop.

Previous research has generally focused only on the pattern-layout phase of the production process. In the manufacture of corrugated cardboard boxes, however, as well as in somewhat analogous cutting procedures in the steel and glass industries, pattern layout is only the first stage in the fabrication of customer orders. Boxes must also be 'finished', i.e. printed, folded and glued according to specifications that vary between product styles. A pattern layout that is near-optimal in terms of trim waste may lead to bottlenecks at a finishing machine which might not have occurred if this latter stage of the process had been considered at the time of scheduling. Unfortunately, common practice in the corrugated box industry is to concentrate on trim waste, and schedule the corrugator with less concern for the finishing operations.

This paper investigates corrugator scheduling procedures which take into account the finishing machines so that customer service, i.e. the achievement of promised due-dates, may to some extent be traded off against trim waste. This treats waste as a factory-wide concept rather than a property of the pattern-layout phase, and is a step in bridging the gap between research literature, plant practice and marketing objectives of the industry.

The remainder of this paper is as follows. The initial section describes the production of corrugated boxes at the plant studied, and includes a discussion of the corrugator and finishing machines. Practical aspects of the cutting-stock problem are examined in the following section. The basic problem is first defined, then the literature is surveyed, focusing on both important formulations and solution methods. We also attempt to reconcile the theory and industry procedures through a brief overview of the major factors to be considered when scheduling the corrugator and the finishing machines in practice. The next section gives a detailed discussion of the simulation model, including some aspects of the modelling process which required special
treatment. Results of experiments conducted through the model are then outlined, while the final section presents conclusions and recommendations for further study.

DESCRIPTION OF THE PRODUCTION PROCESS

Corrugation

The manufacture of corrugated cardboard boxes involves first the production of corrugated sheets, and secondly their conversion into finished cartons through the operations of slitting, printing, folding and closing. The former task is accomplished by fabricating a continuous strip of corrugated board, then cutting it into sheets of customer-specified dimensions. The corrugator forms a linerboard strip, or medium, into a fluted shape, then sandwiches it between two liners to produce single-wall board. There are four common flute styles; the closer together are the flutes, the stronger, thicker and heavier will be the board. Moreover, if the corrugator is 'running double-wall', a second medium and third liner are glued to the single-wall strip. This produces a very strong but heavy board, thus slowing the run time on most machines.

The corrugated strip is next passed over a long set of rollers to allow sufficient time for drying. If the board is too wet or travels this length too quickly to dry properly, the resulting sheets will warp or separate. It is also here that the first trim waste is incurred: because the board's edges are rough and irregular, three-eighths of an inch is removed from each side of the strip. The total amount of this unavoidable waste—three-quarters of an inch times the length of the corrugated strip—can only be reduced by shortening the run length.

The corrugated board is slit into smaller strips corresponding to the specified sheet width, then cut off to yield the sheet length (Figure 1). The cut-off knives are attached to a stationary unit located above the corrugated strip. The slitting knives, however, are mounted on a triple axle, or 'triplex', allowing the knives on one axle to be set while the others are in use. Pegels noted that such changes after each order result in a type of job-shop operation. If the present run length is short, leaving insufficient time to position the triplex knives for the order following, set-up downtime will result.

Most trim waste occurs during the slitting/cut-off stage. The amount of waste is determined by the width of the corrugated strip being produced, so linerboard rolls should be available in a number of different sizes (the Domtar plant studied inventories of nine roll-widths, ranging from 70 to 87 in.). Changing from a wider to a narrower linerboard roll on the corrugator will not generally affect the speed of the machine, but resetting to a larger width often requires that the corrugator be slowed considerably. As with the triplex change-overs, if this change cannot be completed before the end of the present order, the machine will have to be stopped. Moving to a larger width also increases the chance of glue leaking onto the corrugator's rollers, requiring shut-down for cleaning.

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FIG. 1. Cutting and slitting of the corrugated strip.

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Finishing operations

Finishing machines include a wide variety, such as slitters, slotters and printer-slotters. The factory studied in this paper uses only one die cutter and three flexo folder-gluers, but these are adequate to handle many customer orders. Flexo folder-gluers and die cutters are similar: both print, slit, fold and glue the cardboard sheets. However, the die cutter uses a cutting pattern, and is thus employed for cartons of an irregular shape or which require unusual slitting.

After automatically feeding into either machine, the sheets are first printed. A flexible rubber die (like a rubber stamp) is attached to a cylinder which, upon revolving, inks the die and transfers its impression to the sheet. Each cylinder is connected to a different container of ink, so the maximum number of colours available at one time is limited by the number of cylinders.

The printed sheets are next slit and scored, and glue is spread onto the tabs. By moving along a narrow causeway, the sheets are folded in half lengthwise while the tabs are pushed underneath to bond with the opposite ends. The now-finished boxes are strapped into bundles and moved to a central location.

PRACTICAL ASPECTS OF THE CUTTING-STOCK PROBLEM

In order to place our simulation model in context, we summarize some of the analytical approaches to the corrugation stage of the process. Two readily available surveys of the related literature are Golden and Hinxman.

The cutting-stock problem is also referred to as the trim or trim-waste problem; its one-dimensional form is as follows. A factory produces a material such as linerboard in long rolls of fixed width. Customer orders specify a desired number of sheets of a certain length and width. The widths of the cut sheets rarely allow full utilization of the roll, resulting in trim waste (Figure 1) which often is not salvageable. We seek to arrange orders so the sum of sheet widths simultaneously being cut will most closely equal the roll width.

The one-dimensional cutting-stock problem applies to the manufacture of corrugated boxes because the corrugator knives operate independently. Thus, the choice of two orders to be run at the same time is unaffected by the sheet length of either. A feasible solution involves a set of 'cutting patterns' and the number of times each pattern will be used (a cutting pattern is simply a combination of sheet widths whose sum does not exceed that of the roll). Pattern generation can easily become an overwhelming task since corrugator scheduling also requires the sequence in which the chosen patterns will be run.

Sequencing decisions are not part of the usual trim-problem formulation:

\[
\begin{align*}
\text{minimize} & \quad \sum c_j x_j \\
\text{subject to:} & \quad \sum a_{ij} x_j = d_i, \quad i = 1, 2, \ldots, n \\
& \quad x_j \geq 0 \text{ and integer,}
\end{align*}
\]

where \( i \) is an integer which identifies the size (width) of ordered sheet, \( 1 \leq i \leq n; \) \( j \) identifies the cutting pattern, \( 1 \leq j \leq m; \) \( n \) = number of different sheet sizes; \( m \) = number of cutting patterns; \( a_{ij} \) = integer number of sheets of size \( i \) which can be cut using pattern \( j \) once; \( c_j \) = cost of roll from which \( j \)th pattern is cut; \( d_i \) = customer demand for sheet size \( i; \) and \( x_j \) = number of times \( j \)th pattern is applied.

Even without sequencing cutting-patterns, however, this problem is very large: Gilmore and Gomory gave an example where \( m > 10^6 \). They also noted that in the corrugated box industry, customers are willing to accept slight deviations from the quantity ordered, so (2) may be replaced by:

\[
\begin{align*}
\sum a_{ij} x_j & \geq d_i (1 - u) \\
\sum a_{ij} x_j & \leq d_i (1 + w),
\end{align*}
\]

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where \( u_i \) is the maximum acceptable underrun for sheet size \( i \), and \( w_i \) is the maximum overrun. Typical values are \( u_i = 5\% \) and \( w_i = 10\% \).

Gilmore and Gomory expanded the size of problem which could be handled by relating the choice of entering variable in the simplex algorithm to the solution of \( \leq k \) knapsack sub-problems, where \( k \) is the number of roll widths inventoried. With these sub-problems and realistic modifications such as constraints (4) and (5) above, Gilmore and Gomory produced an algorithm which is still considered to be the most powerful available.\(^3\)

One difficulty they noted, however, is that total waste is affected by run length, and thus will usually increase as larger quantities are produced, though percentage waste may decrease. Hence, the objective function, which is no longer linear, should minimize the percentage of waste rather than the amount of it. Yet even this assumes there is no objective besides that associated with trim.

Other difficulties with the minimum waste L.P. solution include the tendency to favor the minimum order quantity when (4) is included, thereby leading to frequent undersupply,\(^5\) the breaking up of orders over the entire production run rather than producing them contiguously,\(^6\) and the ignoring of practical requirements such as relatively few set-ups and long production runs,\(^7\) which severely restricts the number of employable cutting patterns.

Haessler\(^8\) felt it desirable to sacrifice some of the speed of the Gilmore–Gomory algorithm to obtain more control over practical characteristics of the solution. In particular, to avoid undersupply problems when \( x_i \) is rounded down, he added a restriction on the number of times a sheet width could appear in a cutting pattern (if used at all). The algorithm was now slower than before, but the level of trim waste was still comparable.

Dyckhoff\(^9\) presented an L.P. technique involving the a priori generation of a few ‘good’ cutting patterns. This was said to be a more realistic representation of the actual cutting process. Bernhard\(^10\) has suggested that the trim waste could be reduced by inventoring scrap for later use.

**Heuristic methods**

A practical solution procedure must balance the waste objective with customer service, production costs, and machine and workforce utilization. Hinxman\(^1\) noted that many heuristic approaches to the trim problem include criteria (‘aspiration levels’) to decide if a cutting pattern should be used. Moreover, if a pattern is to be used, it will be used as often as possible.

Haessler\(^8\) attempted to limit the number of pattern changes by applying a fixed charge to the use of each pattern. His procedure included restrictions on the minimum and maximum number of sheets per pattern; minimum number of rolls to be processed using the pattern; and the level of trim waste per roll, which could be adjusted to balance raw material and machinery costs. These restrictions may be progressively relaxed until a feasible solution is found.

Unfortunately, many heuristic approaches to the cutting-stock problem have been unsuccessful either because they attempted to generate patterns sequentially and had trouble with trim loss at the end of a sequential procedure, or because they used L.P. to minimize trim, and performed poorly with regard to pattern changes and order congruity.\(^5\)

**Scheduling the corrugator in practice**

Optimization or good heuristic methods essentially minimize trim waste, yet many plants still schedule corrugator production manually. A major reason is that analytic methods usually do not fully capture the problem complexity. It is thus useful to examine factory practice in scheduling and arrangement of orders.

Typically, the corrugator is scheduled daily in preparation for the next day’s production. Scheduling further in advance makes little sense in light of the industry’s dynamic nature; doing so for shorter periods may increase the frequency of style or flute change-overs and yield too small an order set to allow efficient waste control. Customer orders are first grouped based on style, flute or grade. The scheduler decides when to run each group, and arranges those orders, leaving enough flexibility to fit in any high-priority order of a different type. By using (4) and (5) and by breaking large orders into smaller ones, one attempts to run two orders with the same run lengths simultaneously.

Use of roll widths near the maximum width capacity improves corrugator utilization. The wider corrugated strip also leads to a shorter run length and lessens unavoidable trim waste (three-
quarters of an inch times the total run length). The corrugator scheduler generally begins with the widest paper and least amount of trim, then sequences the orders within a particular group from the longest to the shortest run length. Since waste, order-grouping, and length-matching often receive higher priority than due dates, it is not uncommon for an order placed well in advance of its due date to be late.

Scheduling the finishing operations in practice

Most plants try to maintain queues of 4–24 h of work behind each finishing machine. This provides a buffer if the corrugator goes down, and allows the opportunity to run orders of the same flute successively. Set-ups on the flexo folder-gluer can be shortened by reducing the time required to clear the printing cylinders if orders which do not require printing are run first, followed by light-coloured jobs, then dark colours. Also, a long queue gives the corrugated sheets time to dry thoroughly before being slit and folded.

Comments and conclusions

Since the arrangement of orders on the corrugator affects production on the finishing machines, it would be more appropriate to treat waste as a constraint rather than as an objective. The algorithm could then focus on the manufacturing process as a whole rather than on just this one aspect.

Few analytical methods have required that orders be arranged so that raw-material rolls are utilized in sequence of decreasing width. It seems questionable whether any model, no matter how efficient or effective, will be accepted by the industry if this characteristic is not included. Similarly, resetting the machine to a larger roll-width should be done only infrequently to avoid the possibility of downtime while glue is removed from the rollers. Wade11 presented an L.P. approach which scheduled orders in descending width of feed roll required, but, as Pegels1 noted, this additional constraint caused most orders to be broken up, leading to in-process inventory problems.

To adequately meet customer demand, production quantity overruns and underruns should not be likened to a probability distribution with a mean of zero. Two surveys at Domtar, each of about 40 orders, revealed that most orders are scheduled to include about 10% overrun, while underruns are rare. The latter is especially important because several per cent of the corrugated sheets become unusable during the finishing operations. Clearly, a problem with many L.P.-based approaches is that they allow frequent corrugator underruns, but do not restrict the number of such occurrences.

In general, heuristic approaches to corrugator scheduling have had some success because they can more easily be customized to reflect the particular process or factory. Unfortunately, many sequential heuristic methods do well in the early iterations but produce poorer solutions as the order set becomes smaller. The user might correct for this by accepting only part of the schedule and including the rejected jobs in a second, bigger order set. However, this procedure also may lead to the breaking up of a large number of orders.

Therefore, the user should be able to designate an order as one of two types: those which must be sequenced during the current run of the programme, or those which the model can use in order to produce a ‘better’ arrangement but which will not otherwise be scheduled at that time. Determining an appropriate rule for deciding when the second set should be searched is the chief difficulty. This and other aspects of computerized corrugator scheduling algorithms would be assisted by an on-line customer-order data base.

THE SIMULATION MODEL

Introduction

The preceding discussion provides some insight into corrugator scheduling. To investigate the interaction between the corrugator and the finishing machines, we developed a ‘next-event’ simulation model. Orders are input on a daily basis, rather than all at the start of the simulation, and each day’s orders are run on the corrugator before any finishing operations are begun. (Unlike the latter machines, two jobs can be processed on the corrugator simultaneously.) Thus, the set of orders must first be searched as a group to select those which combine well to control trim waste.
After simulating the finishing operations, cumulative results are displayed, and the model requests the next day's orders (see Figure 2).

The model was simplified since only the five style classifications of Table 1 are manufactured at the plant studied. Style E orders, which are placed infrequently and then in small quantities, are usually filled from scrap sheets on the shop-floor and were not simulated. Style D, 'sheet plants', represents all orders which do not require processing beyond the corrugator, i.e. the corrugated sheet is the finished product. Routings are determined by box style (Figure 2).

Times required for machine operations were modelled by assuming that production standards accurately reflect required production times. Randomness is introduced by multiplying that expected value by a variable generated from a positively-skewed beta distribution with mean unity. If, for example, the random variate is less than one, the operation was performed in less time than standard.

**Simulation of the corrugator**

The corrugator can simultaneously cut two different sheet lengths, those of a 'primary' and those of a 'secondary' order. The former must be processed at that given time, while the secondary order

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**Table 1. Simulated style classifications**

<table>
<thead>
<tr>
<th>Style</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Slotted, usually printed, boxes</td>
</tr>
<tr>
<td>B</td>
<td>Die cut, unprinted boxes</td>
</tr>
<tr>
<td>C</td>
<td>Die cut, printed boxes</td>
</tr>
<tr>
<td>D</td>
<td>Unprinted sheets ('sheet-plant orders')</td>
</tr>
<tr>
<td>E</td>
<td>Unprinted pads, liners, folders</td>
</tr>
</tbody>
</table>
is any which has not yet completed corrugation and can be run alongside the primary order to reduce trim. Based upon a user-chosen scheduling rule, a primary order is first selected, and NS, the maximum integer number of sheet widths which can be cut from the given roll width, is calculated. To schedule one primary order, the model loops NS times, at each pass placing one more sheet widthwise along the roll than was used the time before. Attempts are made to choose a secondary order which combines with that number of primary sheet-widths to minimize the waste width for each pass.

Secondary orders are selected from those which have not yet been run as primary orders. Immediately eliminated from consideration is any order which has had all or a substantial quantity completed [see equation (4)], is of a different flute from the primary order, will not fit widthwise onto the roll, or has a sheet length greater than the remaining run length of the primary order. Orders not eliminated by any of these conditions are 'eligible orders'.

For each eligible order, the number of sheet widths which would fit into the trim-waste width is calculated, and the integer result is multiplied by the sheet width. Each iteration yields one potential secondary order, i.e. the order for which the difference between the above product and the waste width is minimized for the given quantity of primary production. Of all potential secondary orders, that which yields the smallest width of trim waste is selected as the final secondary order for that primary order.

Once the secondary order has been selected (or it has been determined that an eligible one does not exist), the waste width is reduced by changing to the smallest of the nine roll-sizes which leaves the minimum positive trim after subtracting the total width of the two orders. The maximum run length of the secondary order is then calculated and compared to the run length of the primary order. The primary order is run to completion if it has the shorter run-length. Otherwise, another secondary order must be chosen before completion of the primary order, which in effect is now being run as two or more smaller orders placed back-to-back. Once all primary orders have been completed, the simulation moves to the finishing operations.

\textit{Finishing operations}

The set-up time of each finishing machine includes adjustments for flute change and for draw-bands (used with very small sheets), determination of ink colour, and allowances for specific make-readies. Occurrences of the former two change-overs are known explicitly from the input data, whereas colour is randomly generated from an empirical distribution. Smaller changes, such as the placement or removal of individual slitting knives, are treated as uniformly distributed random variables since their true distributions are unknown. Also applied is a shift start-up allowance after every 8 simulated hours, and one for complete clean-ups after every 24 h.

Machine-feed standard times depend largely on the area of the corrugated sheet, and can be expressed as a series of step functions of time vs sheet area. Instead of table look-up, an accurate and less memory-intensive method of generating this standard was by a curve fitted to the data by regression. Adjustments to the basic feed standard take into account small order-quantities and palletization of orders. Moreover, standards for the flexo folder-gluer is consider the dimensions of the finished carton.

\textit{Verification and validation}

At each stage of the verification and the validation processes, the output was studied carefully and critically to ensure that it 'made sense'. Domtar initially provided records for 23 shifts of production, consisting of detailed characteristics of about 300 orders and shift reports for each of the five machines. This data allowed better estimation of a number of parameters. Also, for each machine, the actual order-processing times given by or estimated from the shift reports could be compared to results obtained when the same orders were run through the model. Such testing showed that actual processing times for all machines could be modelled accurately through the use of the standards. This conclusion was also supported by summary statistics which compared actual performance with that estimated by the standards for the entire past year.

To obtain a feel for the relative waste-control capabilities of the corrugator routine, our model was applied to a case in which published results of other models were available. Pegels\textsuperscript{1} compared
the performances of three early computerized corrugator scheduling models—those by Van Duyne,11 Van Wormer12 and Wade13—through use of a simple eight-order example. His article included sufficient detail as to customer-order characteristics and raw-material sizes to run his example through the present model.

Our model yielded a waste figure of 3.37%, comparable to results reported by Pegels for the heuristics of Van Duyne (3.53% waste) and of Van Wormer (3.01% waste), and to the L.P. approach of Wade (2.87% waste). Moreover, our model produced a smaller quantity underrun than did Van Duyne's heuristic. A more detailed discussion is in Higginson.14

SIMULATION RESULTS

Customer-order characteristics used for model production runs were computer-generated from empirical and theoretical probability distributions. From analysis of the 300 customer orders supplied by Domtar, distributions were chosen for each of six characteristics of customer orders: product style, flute, sheet length, sheet width, order quantity and due date (lead time). The first two characteristics were handled as empirical distributions based on observed orders. The latter four characteristics, sub-divided by style, were adequately fit by theoretical distributions such as normal, uniform and Erlang.14

Scheduling rules

The model included 12 possible scheduling rules. Four which were investigated in the production runs were: rule No. 3, "by flute, then decreasing sheet width"; rule No. 7a, "by flute, then earliest due-date"; rule No. 7b, "by flute, then earliest due-date, then decreasing sheet width"; rule No. 9, "by earliest due-date, then flute, then decreasing sheet width".

Rule No. 3 should result in the smallest amount of waste: when packing or arranging objects, it is intuitively more efficient to place larger items first and use smaller ones to fill the remaining space. Although rule No. 3 ignores customer service, it does group production by flute. Other than changing between running double-wall and single-wall sheets, a flute change is probably least desirable of all individual corrugator set-up items, requiring upwards of 50% of total set-up time. Planned corrugator flute-changes thus occur in practice only 3 or 4 times daily, so a realistic scheduling criterion should include some grouping by flute.

Rule No. 9 considers customer service, but by placing the earliest due-date criterion ahead of that of flute, the potential number of flute changes is increased beyond that of rule No. 3. Rule Nos 7a and 7b act as a type of 'middle road' between rule No. 3 and rule No. 9: they would be expected to yield less satisfactory customer service levels than rule No. 9 since they put less emphasis on the earliest due-date criterion. Moreover, the inclusion of both rule Nos 7a and 7b allowed investigation of the effect of the third scheduling criterion, "by decreasing sheet width".

Two additional scheduling rules were studied: rule No. 10, "by flute, with all sheet-plant orders run before box orders each day"; and rule No. 11, "by flute, with all box orders run before sheet-plant orders each day". It is common practice at some plants to corrugate all box orders successively, then all sheet-plant orders. This approach, described by rule No. 11, permits lengthy queues to develop at the finishing machines while the corrugator is on box production and then to lessen during sheet-plant production. Machine crews are thus more efficiently utilized by being continually busy at the same work station for longer periods of time.

Confidence intervals

One method of determining confidence intervals for the mean performance level in steady-state simulation is by batch means.15 This technique divides the output data into small groups, the mean of each being an approximately independent and identically distributed observation. Classical statistical methods can then be applied.

For each scheduling rule above, 6000 orders were simulated. The logical batch size was one day since, in practice, performance is measured on a daily basis, and 60 orders per batch was concluded to be approximately equivalent to one day's production on the corrugator. Common random numbers were employed in an attempt to reduce the variance between paired observations when comparing two rules. Statistics were collected for measures such as percentage waste, percentage
orders late, and mean time late of late orders. These results are summarized in Table 2 and Figure 3.

Waste vs customer service

A substantial number of paired-\(t\) tests were performed. Certain obvious similarities were found, e.g. percentages of orders late under rule No. 10 and rule No. 11. The difference between customer service measures of any two alternative rules was generally statistically significant at both the 90 and 95% levels.

Results for percentage waste were less definitive. At the 95% confidence level, there was no statistical difference in mean daily waste for rule Nos 7b, 9 and 10, while rule Nos 7a and 10 and rule Nos 7b and 11 were concluded to produce different levels of waste.

As was hypothesized, rule No. 3, which emphasized control of waste, yielded the lowest percentage waste of all six rules. With regard to both customer service measures, however, it produced the poorest performance of the four rules which segregate by product style. By emphasizing customer due-dates, rule No. 9 gave the best customer-service results, although its

![Figure 3. Percentage waste vs % daily orders late.](image)
mean percentage waste measure was about one half of one per cent (in absolute terms) greater than that of rule No. 3. A clear trade-off between waste and customer service can be seen in these results.

For percentage waste and customer service, rule No. 7b outperformed rule No. 7a, its twin without a sheet-width criterion. Thus, the extra scheduling factor did play an active role in reducing waste. Moreover, rule No. 7b appears somewhat to be a “middle road” between rule Nos 3 and 9; rule No. 7a obviously does not fit this description. There was, however, no statistical difference in percentage waste values yielded by rule Nos 7b and 9.

When the six rules are taken as a whole, the dominant conclusion of Figure 3 is that there is not a clear-cut relationship between waste and customer service. However, the results of rule Nos 3, 7b and 9 do create an interesting “efficient set”; rule Nos 7a, 10 and 11 form a less desirable but internally non-dominated group. Considered separately, both of these sets illustrate that a reduction in waste can, in fact, mean poorer customer service.

The performance of rule Nos 10 and 11 relative to the other four was surprising: a better showing had been expected of each with regard to waste and to customer service. The higher percentage waste figures are perhaps easily understood: neither rule made any explicit attempt to control waste. Extending the two rules to include a sheet-width criterion, then, might provide interesting results when compared to those of rule No. 3, which does not segregate orders by product style, as do rule Nos 10 and 11. This is left to further research.

As noted earlier, some plants employ rule No. 11: each day, box orders are run before sheet-plant orders. By segregating orders by product style, job queues at the finishing machines are quickly created or lengthened during box-order production, and gradually disappear while sheet-plant orders are being corrugated. Unfortunately, the existence of queues may cause the appearance of two detrimental factors. First, as the faster machines backlog, some orders will be routed to slower ones. More importantly, job queues at the finishing machines cause machine set-up times to become relevant.

In practice, machine crews receive detailed instructions regarding each order before it arrives at their station. Thus, if idle time occurs between jobs, it is possible to begin preparing for the next order. Rule Nos 3, 7a, 7b and 9—all of which mix boxes and sheets—are likely to cause frequent, though short, periods of idle time. However, by creating machine backlogs, rule Nos 10 and 11 reduce the number of these occurrences, though not necessarily the total amount of idle time. Clearly, set-up times will play an active role in the meeting, or missing, of order due-dates, depending upon whether the corrugator schedule creates some, little or no idle time at the finishing machines.

CONCLUSIONS

A non-linear trade-off between waste and customer service is partially illustrated by the results of rule Nos 3, 7b and 9. Scheduling orders by rule No. 3, “by flute, then decreasing sheet width”, produced the lowest mean daily waste, but also performed less favourably with regard to customer service. Conversely, rule No. 9, “by earliest due-date, then flute, then decreasing sheet width”, reported the best customer service results, though at the cost of higher waste. An attempt to compromise the two rules through use of rule No. 7b, “by flute, then earliest due-date, then decreasing sheet width”, yielded a daily orders-late statistic midway between that of the other two rules, but left waste at approximately the higher value. The overall relationship is more complex, and an improvement or deterioration in one measure will not necessarily have the opposite effect on the other.

Segregating orders by product style before scheduling gave poorer waste and customer service results than did rules which mixed box orders and sheet orders. This would indicate it is undesirable to separate orders by product style at the corrugator, even though this practice may improve workforce utilization and flexibility in sequencing orders at the finishing machines. Unfortunately, such benefits are not readily seen through the simulation, partly because the scheduling rules which separated product styles were less detailed than those which did not. Extending the former rules to include further criteria may yield improved waste or customer service outcomes. Moreover, if the simulation’s corrugator routine were improved to incorporate more realistic criteria for determining at what point the roll width should be reset to the widest size, our model could be
used to investigate the feasibility of inventorying fewer raw-material sizes. Diegel and Bocker\textsuperscript{16} have recently studied analogous questions in the glass industry.

It was not the intention of this paper to create an improved algorithm for the cutting-stock problem. In practice, an experienced scheduler can reduce waste to as low as 2\%, while state-of-the-art trim algorithms achieve about 2.5\% waste. Our heuristic scheduling rules yielded waste in the range of 2.8–3.5\%, which, considering the simplicity of these rules, seems quite reasonable. Whether an additional 0.5\% of trim waste is acceptable in exchange for a 3\% improvement in customer service is a question left to management.

Lastly, the most important component of any approach to scheduling is flexibility, both in creating the initial schedule and when reacting to potential changes throughout the day. Computerized cutting-stock algorithms are useful as decision aids, but it seems unlikely that any of the present models will completely replace the human scheduler. Our stochastic simulation model allowed no human intervention during a run; the required large number of simulated days made this prohibitive. However, once a scheduling rule has been selected based on favourable performance for a random set of customer orders, the problem is deterministic: today's actual orders are scheduled by that rule. Inclusion of the better rules for use in an interactive framework with an on-line customer-order data base would be a major project of future interest.

Acknowledgements—This work received generous support from the Packaging Division of Domtar Inc. We owe special thanks to Ray Chow, Lee Chan and Nazir Premji of Domtar.

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