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CUTTING AS A CONTINUOUS BUSINESS PROCESS

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ABSTRACT: *A review of state-of-the-art methods for cutting stock problem optimisation shows that the current methods lead to near-optimum results for the instantaneous optimisation of trim loss. Further optimisation of this activity would not bring a considerable improvement. Therefore, the paper treats cutting stock as a continuous business process and not as an isolated activity. An exact method for a general one-dimensional cutting stock problem is presented and tested. The method is mainly suitable for smaller orders. It is then applied to continuous cutting and used to develop a method for assessing cutting costs in consecutive time periods. The modified method finds a good solution over the whole time-span, rather than just local optima.*

Key words: *Cutting stock problem; Continuous cutting; Supply chain management; Exact solution; Business process management*

UDK: 005.81:004

JEL classification codes: C61, D81, L23

1. INTRODUCTION

The cutting stock problem ('CSP') was first defined more than 50 years ago (Paull, 1956) and has since then attracted many researchers. There has been a rise in research interest in this topic over the last decade when many different versions of the model and solution approaches have been studied (e.g. Trkman, Gradišar, 2007). Since near optimum solutions with a trim loss of less than 0.1% have been found (Gradišar, Trkman, 2005) the research interest has shifted to lowering the overall costs of the cutting process.

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As the research goals have diverted away from optimising only trim loss, the consideration of cutting stock as a process instead of just an isolated activity has become more important. With the advent of concepts such as lean manufacturing and supply chain integration cutting orders are becoming smaller and thus exact methods can easily be used. We therefore develop an exact method for solving the CSP and integrate it into a broader view of the cutting stock process. The importance of treating the cutting stock process as a continuous business process and its effects on a decrease in overall costs is also presented.

The structure of this paper is as follows. In the second section the CSP is defined and different approaches to solving it in the past are presented. The third section presents an exact solution method suitable for CSPs with smaller orders. The next section defines cutting as a business process and emphasises the importance of treating cutting as one of the processes in the company and in the supply chain. The fifth section broadens the view by adding in the time component while the last section summarises the paper and points to topics for further research.

2. THE CUTTING STOCK PROBLEM

There are many different variations of the CSP in practice since it is common in a range of industries. The materials used for cutting can take many different shapes, from rolls, scrolls, coils, plates, logs etc. The basic problem is how to cut the material in stock into the desired number of ordered pieces while at the same time minimising the trim loss which results from the cutting (Gass, 1985). The stock can consist of materials of different dimensions. The cutting can then be done on several different cutting machines. The knives of each cutting machine can be set to any combination of orders so that the entire length of orders does not exceed the length of the piece from stock. The orders are defined as the number of pieces of a certain dimension or the total length needed for one order.

There are different types of cutting stock problem with regard to the number of dimensions. The most frequently researched one is the problem of one-dimensional cutting. In this paper we focus on the latter. However, the main point that CSP optimisation should include the whole process can also be applied to other types of cutting (two-, three- or even four-dimensional). With one-dimensional cutting only one dimension is significant as the other dimensions are fixed, negligible or do not even exist (for example the »cutting« of time, money etc.).

Approaches to solving the one-dimensional cutting stock problem can be divided into two main groups (Dyckhoff, 1990):

- The pattern-oriented approach: cutting patterns and their frequencies are defined by different methods. Most are based on the algorithm presented by Gilmore and Gomory (1961, 1963). These methods are only usable if all the items in stock are of the same length or if there are only a few standard lengths in stock.

- The item-oriented approach: each piece from stock is treated individually when preparing the cutting plan whereas with the pattern-oriented approach only patterns are defined. Methods that utilise the item-oriented approach have a broader aspect of usability since they can be used with either standard or non-standard stock lengths.

Pattern-oriented approaches are therefore more useful and flexible with larger problems of standard lengths of stock pieces, while item-oriented approaches are applicable to different lengths of stock pieces. Both approaches utilise two different methods: exact and heuristic.

Exact methods are based on algorithms which lead to the optimal solution of the problem, which is their main advantage. However, the time needed for solutions increases exponentially, meaning they are limited to smaller problems. The most commonly used methods for exact solutions are linear programming, branch and bound method and dynamic programming.

Heuristic methods lead to near-optimum solutions and are usually better at solving larger problems. Heuristic methods take different approaches to problem-solving: state-space search, problem reduction, cut-off, aspiration level, repeated exhaustion reduction, sampling (Hinxman, 1980; Nilsson, 1971).

Several methods were developed in the past using the different approaches mentioned above. Some of them solve the basic cutting problem by minimising the trim loss while others expand the initial cutting stock problem to additional criteria. The more interesting ones are the integer programming model applying the branch & bound ('B&B') approach used by Degraeve and Vandebroek (1998), cutting non-standard lengths (Belov, Scheithauer, 2002), cutting materials of different quality (Carnieri et al., 1993), minimising the number of patterns used for cutting (Umetani et al., 2003; Vanderbeck, 2000), minimising the costs of changing the patterns (Shilling, Georgadis, 2002), multiphase methods (Zak, 2002) etc. Also interesting are methods developed for specific industries such as the steel industry (Armbuster, 2002), wood industry (Čižman, Urh, 2006), metal industry (Chu, Antonio, 1999) and car industry (Dowsland et al., 2007).

3. EXACT SOLUTION

Most standard problems related to one-dimensional stock cutting are known to be NP-complete and in general a solution can be found by using approximate methods and heuristics. However, the constantly growing processing power is pushing the complexity limit for exact methods up slightly.

The most important factor in the usability of exact solutions is the size of the problem. More information (future orders, available supply, lead times etc.) is available by treating cutting as one of the business processes in the entire supply chain. This enables greater flexibility when determining the size of orders and can lead to smaller orders (Muffato, Payaro, 2004), thus making them more suitable for exact methods. Therefore we present an exact solution of general one-dimensional cutting stock problem (G1D-CSP) where all stock lengths can be different.

Either the branch & bound ('B&B') method or some dynamic programming can be used. The B&B exact method was chosen. First, B&B is a standard method and, second, many OR packages with B&B exist. Some of them allow the use of B&B as a subroutine so it can be included in other computer applications. In our case, it is included in an application which collects data, checks whether there is an abundance or shortage of material, solves the appropriate model and displays the results.

The problem is defined as follows:

For every customer order a certain number of stock lengths is available. In general all stock lengths are different. We consider the lengths as integers. If they are not originally integers we assume that it is always possible to multiply them by a factor and transform them into integers. It is necessary to cut a certain number of order lengths into the required number of pieces. The following notation is used:

s_i = order lengths; $i = 1,...,n$.
b_i = the required number of pieces of order length s_i.
d_j = stock lengths; $j = 1,...,m$.
x_{ij} = the number of pieces of order length s_i having been cut from stock length j.
UB = the upper bound for the trim loss
t_j = the extent of the trim loss relating to stock length d_j)
δ_j = the remainder of the stock length d_j

Two cases are possible:
Case 1: the order can be fulfilled as an abundance of material is in stock.

$$\min \sum_{j=1}^{m} t_j \quad \text{(minimise the trim loss which is smaller than } UB\text{)} \tag{1}$$

s.t.

$$\sum_{i=1}^{n} (s_i \times x_j) + \delta_j = d_j \forall j \quad \text{(knapsack constraints)} \tag{2}$$

$$\sum_{j=1}^{m} x_{ij} = b_i \forall i \text{ (demand constraints – the numbers of pieces are all fixed)} \tag{3}$$

$$\sum_{i=1}^{n} x_{ij} + \frac{\max d_j}{\min s_j} \times (y_j - 1) \leq 0 \forall j \quad \text{(} y_j \text{ indicates whether stock length } j \text{ is not used in the cutting plan)} \tag{4}$$

$UB - \delta_j + UB \times (u_j - 1) \leq 0 \forall j$ (u_j indicates whether the remainder of stock length j is greater than UB) (5)

$$\sum_{j=1}^{m} u_j \leq 1 \text{ (the maximum number of residual lengths that can be larger than } UB\text{)} \quad (6)$$

$$\delta_j - t_j - (u_j + y_j) \times (\max d_j) \leq 0 \forall j \quad (7)$$

$$UB \geq \max s_j \quad (8)$$

$$x_{ij} \geq 0, \text{ integer } \forall i, j \quad (9)$$

$$t_j \geq 0 \forall j \qquad \delta_j \geq 0 \forall j \qquad u_j \in \{0,1\} \qquad y_j \in \{0,1\} \quad (10)$$

If $\sum_{i=1}^{n} x_{ij} > 0$ then according to condition (4) $y_j = 0$. If $\sum_{i=1}^{n} x_{ij} = 0$ this allows either $y_j = 0$ or $y_j = 1$. Since $y_j = 1$ is less costly than $y_j = 0$, the optimal solution will choose $y_j = 1$ if $\sum_{i=1}^{n} x_{ij} = 0$. In summary, we have shown that $\sum_{i=1}^{n} x_{ij} > 0$ will imply $y_j = 0$ and $\sum_{i=1}^{n} x_{ij} = 0$ will imply $y_j = 1$. Condition (5) can be explained similarly.

Case 2: the order cannot be fulfilled entirely due to a shortage of material (the distribution of uncut order lengths is not important).

$$\min \sum_{i=1}^{n} \delta_j \text{ (minimise the sum of trim losses)} \quad (1)$$

s.t.

same as in case 1 (2)

$$\sum_{j=1}^{m} x_{ij} \leq b_i \forall i \text{ (demand constraints)} \quad (3)$$

$$x_{ij} \geq 0, \text{integer } \forall i, j \quad (4)$$

$$\delta_j \geq 0 \forall j \quad (5)$$

Unutilised stock length that is larger than some *UB* could be used further and is not considered as waste. The question is how to determine *UB*. The answer depends on the quantity of stock lengths available.

Let us consider case 1 first. If sufficient stock lengths are available there will be cutting plans with "no trim loss" but ever growing stocks. To prevent this, an additional condition (case 1, condition (6)) has to be set: only one residual length may be longer than the *UB*. *UB* can be set arbitrarily between 0 and max s_i. UB = min s_i is found in practice (Gradišar et al., 1997).

However, in case 2 *UB* is not included in the model. If, for example, *UB* is reduced to min s_i this would lead to the following problem: as the aim of the algorithm is minimisation of the overall trim loss this could lead to unfulfilled requirements for the longest order lengths, even if the overall trim loss is small and the aim is achieved according to the logic of the algorithm. Trim losses which would be longer than *UB* but shorter than the longest order lengths could remain unutilised. For that reason, *UB* should not be less than max s_i. On the other hand, if *UB* were set to max s_i any trim loss longer than max s_i can certainly be used to cut an additional order length so *UB* equal or longer than max s_i would not have any influence on the solution.

The method was tested on 270 problem instances, namely, 150 with an abundance and 120 with a shortage of material. To test the correlation between the time limit and trim loss each problem instance in the experiments was solved within six different time limits. All problems with an abundance of stock were solved twice – once with *UB* set to max s_i and once with *UB* set to min s_i. The results with *UB*=min s_i are shown in Table 1, while full results can be found in (Gradišar et al., 2002). The "opt" column shows the number of optimally solved problems within the given time limit (each problem class contained 10 problem instances). A comparison of the exact method with state-of-the-art heuristic methods is shown in Table 2. The results show the approximate limit of the usability of the exact method. Since the size of the problems in section 5 is below that limit the exact method is used.

TABLE 1: *Results for UB= min s_i*

Case no.	2 seconds			10 seconds			20 seconds			30 seconds			45 seconds			60 seconds		
	Trim loss			Trim loss			Trim loss			Trim loss			Trim loss			Trim loss		
	cm	%	opt	cm	%	opt	cm	%	opt	cm	%	opt	cm	%	opt	cm	%	opt
1	1	0.0027%	9	1	0.0027%	10	1	0.0027%	10	1	0.0027%	10	1	0.0027%	10	1	0.0027%	10
2	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10
3	3	0.0026%	8	1	0.0009%	9	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10	0	0.0000%	10
4	1301	1.6761%	5	1028	1.3445%	9	1028	1.3445%	9	1028	1.3445%	9	1028	1.3445%	9	1028	1.3445%	9
5	831	0.4978%	0	351	0.2119%	1	295	0.1759%	2	255	0.1495%	2	228	0.1327%	2	212	0.1229%	2
6	852	0.3552%	0	295	0.1240%	0	83	0.0364%	1	69	0.0301%	1	62	0.0269%	2	62	0.0269%	2
7	1702	2.3912%	9	1702	2.3912%	10	1702	2.3912%	10	1702	2.3912%	10	1702	2.3912%	10	1702	2.3912%	10
8	2884	1.3326%	0	2325	1.0791%	0	1755	0.8112%	0	1541	0.7116%	0	1519	0.6996%	0	1457	0.6706%	0
9	4103	1.1964%	0	3045	0.8837%	0	2555	0.7473%	0	2201	0.6467%	0	1911	0.5595%	0	1780	0.5196%	0
10	157	0.2295%	1	53	0.0730%	2	27	0.0383%	3	27	0.0383%	3	22	0.0305%	4	18	0.0246%	5
11	96	0.0671%	2	25	0.0164%	4	10	0.0065%	6	10	0.0065%	6	8	0.0052%	6	8	0.0052%	6
12	269	0.1189%	0	83	0.0372%	7	64	0.0285%	7	39	0.0175%	8	27	0.0122%	8	23	0.0103%	8
13	99	0.1245%	2	41	0.0515%	4	33	0.0419%	4	17	0.0219%	5	9	0.0113%	6	8	0.0100%	6
14	3022	1.0156%	0	2048	0.6839%	0	1703	0.5687%	0	1666	0.5572%	0	1666	0.5572%	0	1613	0.5393%	0
15	6652	1.4417%	0	2753	0.5913%	0	2565	0.5483%	0	2502	0.5334%	0	2324	0.4923%	0	1833	0.3866%	0
16	266	0.3686%	1	114	0.1569%	5	49	0.0681%	8	49	0.0681%	9	49	0.0681%	9	49	0.0681%	9
17	4011	1.3846%	0	3013	1.0466%	0	2630	0.9136%	0	2580	0.8953%	0	2272	0.7893%	0	2074	0.7236%	0
18	9599	1.6617%	0	7936	1.2251%	0	7041	1.0860%	0	6533	1.0099%	0	6533	1.0099%	0	6533	1.0099%	0
19	29	0.0402%	5	10	0.0142%	9	5	0.0071%	9	3	0.0043%	9	0	0.0000%	10	0	0.0000%	10
20	1179	0.5150%	0	756	0.3203%	0	638	0.2707%	0	557	0.2361%	0	434	0.1827%	1	429	0.1803%	1
21	7753	2.1027%	0	1143	0.3401%	0	600	0.1691%	0	568	0.1599%	0	444	0.1235%	1	438	0.1217%	1
22	141	0.1831%	4	37	0.0477%	5	21	0.0275%	7	4	0.0051%	8	1	0.0013%	9	1	0.0013%	9
23	2580	0.8612%	0	1941	0.6456%	0	1551	0.5126%	0	1357	0.4517%	0	1071	0.3559%	0	1043	0.3468%	0
24	16250	3.0632%	0	13977	2.3567%	0	7639	1.1572%	0	7101	1.0736%	0	6856	1.0387%	0	5615	0.8531%	0
25	427	0.5728%	1	113	0.1457%	2	93	0.1197%	2	93	0.1197%	2	48	0.0636%	2	41	0.0549%	3
26	2037	0.6872%	0	1319	0.4446%	0	1054	0.3547%	0	1054	0.3547%	0	993	0.3325%	0	984	0.3294%	0
27	11150	1.6180%	0	7518	1.0954%	0	5984	0.8730%	0	5984	0.8730%	0	5859	0.8553%	0	5316	0.7742%	0
Totals	**77394**	**0.8707%**	**57**	**51628**	**0.5678%**	**87**	**39126**	**0.456%**	**98**	**36941**	**0.4334%**	**102**	**35067**	**0.4106%**	**109**	**32268**	**0.3895%**	**110**

TABLE 2: *Trim loss with an exact method after 60 seconds and with the CUT procedure*

	Abundance of material	Trim loss CUT		Trim loss B&B	
Case no.		cm	%	cm	%
1	Y	8	0.0213%	1	0.0027%
2	Y	0	0.0000%	0	0.0000%
3	Y	0	0.0000%	0	0.0000%
4	Y/N	1182	1.5460%	1028	1.3445%
5	Y	28	0.0162%	212	0.1229%
6	Y	9	0.0039%	62	0.0269%
7	N	1940	2.7256%	1702	2.3912%
8	Y	213	0.0980%	1457	0.6706%
9	Y	285	0.0832%	1780	0.5196%
10	Y/N	59	0.0807%	18	0.0246%
11	Y	0	0.0000%	8	0.0052%
12	Y	2	0.0009%	23	0.0103%
13	N	88	0.1103%	8	0.0100%
14	Y/N	172	0.0575%	1613	0.5393%
15	Y	22	0.0046%	1833	0.3866%
16	N	227	0.3155%	49	0.0681%
17	N	272	0.0949%	2074	0.7236%
18	Y/N	541	0.0836%	6533	1.0099%
19	N	7	0.0095%	0	0.0000%
20	Y	10	0.0042%	429	0.1803%
21	Y	0	0.0000%	438	0.1217%
22	N	47	0.0618%	1	0.0013%
23	N	36	0.0120%	1043	0.3468%
24	Y	159	0.0242%	5615	0.8531%
25	N	81	0.1085%	41	0.0549%
26	N	93	0.0311%	984	0.3294%
27	N	112	0.0163%	5316	0.7742%

Source: (Trkman, Gradišar, 2003a)

4. CUTTING AS A BUSINESS PROCESS

However, most of the reviewed methods for cutting optimisation try to optimise only the traditional criteria for the suitability of the solutions which are: trim loss, overproduction, average inventory level, average number of different order lengths and average number of different stock lengths (Venkateswarlu, 2001). Contemporary cutting stock solutions already lead to near-optimal results for such problems (for example, Gradišar et al., 2002a) and therefore research attention has been diverted to solutions with other goals (Trkman, Gradišar, 2003; Yang et al., 2006), such as total cutting costs, cutting time, opportunity costs etc. Most criteria are limited to a single activity (cutting) in a process. This opens up several research topics since the relevance of multiple criteria for evaluating supply chain efficiency has been emphasised (Meixell, Gargeya, 2005). In addition, the value of information technology implementation and other changes should be measured at the process level (Davamanirajan et al., 2006).

Our paper therefore presents a novel approach to treating the CSP as a business process. Treating cutting as one of the processes in the company is in accordance with research findings that companies with a higher level of business process maturity outperform companies with less business process maturity (Lockamy, McCormack, 2004; Škrinjar et al., 2007).

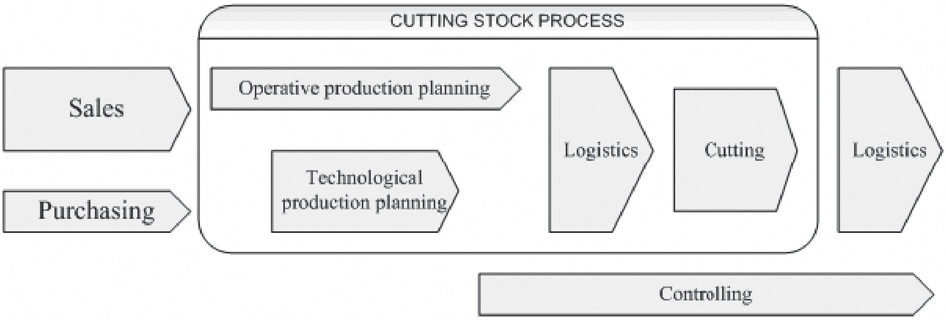
Business process is defined as a sequence of logically connected activities which are necessary to achieve wanted business outcomes (Srivardhana, Pawlowski, 2007; Davenport, Short, 1990). It is also defined as a structure of logically connected executing and controlling activities that produce a product or a service as an outcome (Kovačič et al., 2004). If an activity can be defined as a process of its own it is called a sub-process. A sub-process is therefore a collection of interrelated activities within a larger process. Activity is the basic unit of a process for which it is no longer reasonable to divide it into smaller parts. Depending on the industry the cutting process can be one of the core operational processes or just a supporting process for one of the core processes. Cutting is the core process in companies whose main service is cutting (for example, saw mills). As a sub-process it is involved in many industrial companies where materials need to be cut from larger parts. The importance of the cutting process is thus related to the type of industry and company involved.

The cutting process itself consists of several activities. The level of dividing the cutting process into smaller activities mainly depends on the purpose of modelling. For example, activities in the cutting (sub)process can be the following: acceptance of the order, moving materials from the warehouse to the place of cutting, preparation of the cutting plan, returning unused material to the warehouse etc.

It is important to model processes to better understand them, including the cutting process. The modelling involves converting all activities and knowledge about the business system into models which describe the processes within the organisation (Scholz-Reiter, Stickel, 1996; Giaglis, 2001). Processes are usually modelled in order to be redesigned.

What is important to note here and can be seen in Figure 1 is that the cutting should be viewed as only one of the activities or a sub-process which is connected with other processes and activities in the company and the entire supply chain (Erjavec et al., 2009). Only then can optimisation of the cutting itself lead to lowering the costs of the process of making new products or creating added value.

FIGURE 1: The cutting stock process in connection to other processes in the company



Source: Erjavec et al., 2008

The successful co-ordination of business processes and supply chain management is important for certain factors that are key to optimising the cutting, for example:

- E-procurement can bring a decrease of 42%-65% in purchasing transaction costs and a similar decrease in lead times (Davila et al., 2003; Presutti, 2003). This means that a company can order and deliver smaller quantities of materials. Different cutting optimisation methods are therefore required (for example, the exact method described in the following section).
- A successful information interchange between companies in the supply chain can lead to a decrease in the uncertainty of future demand which leads to a better basis for stock planning and less cutting waste. It also lowers the risk of order non-fulfilment.
- Successful cutting process harmonisation within the supply chain can ease mass customisation (see e.g. Trkman, Gradišar, 2002).

The examples shown above are a consequence of better supply chain management in the entire supply chain. It has been proven that optimisation of the whole chain can namely bring about considerably better results than the optimisation of processes within a single company (Trkman et al., 2007; Kobayashi et al., 2003).

5. CONSECUTIVE CUTTING

Most approaches treat cutting as a one-off activity while, in reality, it is more likely to be a continuous business process. This opens up a new research field and a number of research questions for both research and practical use since several new factors connected to business processes have to be taken into consideration. Therefore, the development of methods, similar to the one described in this section, is vital. Further important research questions are outlined in the last section.

There is a constant flow of incoming stocks and orders that need to be fulfilled with the company often having the ability to affect the size of the ordered stocks while, on the other hand, being able to anticipate future orders. Consecutive cutting is thus the periodical cutting of materials, replenishing stocks and anticipating future orders. The main goal is to minimise the sum of costs in all time periods. It is therefore important for companies to treat cutting as a business process and evaluate its costs compared to the cutting itself (Erjavec et al., 2009).

Not many papers deal with cutting in the way described above. One of the first approaches is presented in Trkman, Gradišar (2007) where the authors deal with nine consecutive periods of time in which cutting is commenced and stocks are replenished while the number of pieces returned to the stock is unlimited. Two different approaches are used in the paper to minimise overall losses. Both are summarised later in this section. In order to assess the effectiveness of both approaches we compared them with the exact method described in section 3 herein and two other methods (Gradišar et al., 1999; Gradišar, Trkman, 2005), as shown in Table 3.

TABLE 3: *Basic strengths and weaknesses of each method*

Method	Strength	Weakness
CUT	Fast solving, suitable for large problems	Solution is not always optimal
C-CUT	Relatively fast solving, suitable for large problems	Solution is not always optimal, but usually better than CUT
Exact	Leads to the optimal solution for smaller problems (e.g. with consecutive cutting)	Not usable for larger problems
Consecutive cutting – model 1	Average solving speed, lower loss in the optimal solution because of looser restrictions	Leads to a large amount of partially cut pieces and consequently higher costs of warehousing and problems with later cuttings. Not suitable for consecutive cutting.
Consecutive cutting – model 2	Average solving speed No saturation of stock with partially used stock lengths over time periods – a smaller number of partially cut pieces returned to stock Suitable for consecutive cutting	No benchmark testing is possible as this is the first method proposed for such a problem

Since the first approach in Trkman, Gradišar (2007) (Consecutive cutting – model 1) is unsuitable because of the steep rise in the amount of pieces returned to stock[1] the authors suggest another approach. The costs of returning the partially cut pieces are now considered. This lowers the total amount of partially cut pieces returned to stock (Consecutive cutting – model 2). The results of the second approach can be seen in Table 4.

[1] The number of pieces returned to stock is not limited. Therefore, many shorter ones are returned to stock and their amount rises throughout periods of time.

TABLE 4: *Results for consecutive cutting – model 2*

UB \ Period	Per 1	Per 2	Per 3	Per 4	Per 5	Per 6	Per 7	Per 8	Per 9	Total
400	0/20/4/3	1/22/5/0	0/20/8/2	7/54/10/60	0/20/12/1	0/20/14/12	5/50/16/60	0/0/16/1	4/28/18/60	**17/234/18/200**
600	0/20/4/2	1/22/5/0	0/20/8/5	0/40/10/60	0/20/12/2	6/32/14/60	6/120/16/60	9/18/19/35	12/164/20/60	**34/456/20/285**
800	0/20/4/0	0/20/5/0	0/20/8/16	13/66/10/60	0/0/12/0	0/10/14/2	13/226/16/60	0/20/16/5	2/24/18/60	**28/406/18/203**
1000	0/20/4/0	0/20/5/0	0/20/8/8	4/88/10/60	0/0/13/1	0/20/14/10	7/74/16/60	0/20/17/25	9/38/19/60	**20/300/19/224**
1200	0/20/4/0	0/20/5/0	0/20/8/8	7/134/10/60	0/20/13/4	8/16/15/6	4/88/16/60	0/20/15/15	8/76/18/60	**27/414/18/214**
1400	0/20/4/0	0/20/5/0	3/26/8/20	6/92/9/60	0/20/12/5	0/20/14/15	0/20/16/60	0/20/16/38	8/56/18/60	**17/294/18/258**
1600	0/20/4/0	0/20/5/0	3/26/8/60	0/40/9/60	0/20/11/1	0/20/13/7	0/20/15/60	0/20/14/7	0/20/16/60	**3/240/16/255**
1800	0/20/4/0	0/20/5/0	3/26/8/60	0/80/10/60	0/20/13/2	0/20/15/11	3/66/17/60	0/20/16/28	0/40/18/60	**6/312/18/282**
2000	0/20/4/0	0/20/5/0	0/20/8/6	0/60/9/60	0/0/11/0	0/20/13/5	1/22/15/60	0/20/15/8	0/120/17/60	**1/302/17/198**

Source: Trkman, Gradišar (2007)

Table 4 shows the trim loss as the first value, the sum of the trim loss and return costs as the second value, the number of stock lengths at the end of period as the third value and computation time (in seconds) as the fourth value for different values of *UB* in each of the nine time periods. All problems are solved within the time limit of one minute. The number of stock lengths does not increase significantly and the costs of the trim loss and return costs stay around the same level over all nine periods.

This deviation of costs from period to period is likely due to coincidence. In specific demand and supply patterns (e.g. if the ratio between total supply and total demand were to increase considerably) a decrease in later time periods would be possible (or vice versa). See (Trkman, Gradišar, 2003) for a detailed analysis of factors that affect the quality of solutions. Unfortunately, the number of examples solved in this paper does not allow a full analysis of changes in time; it would also be beyond the scope of the paper.

As such, the method is suitable for cutting in consecutive time periods. With the described modification of the model local "optimums" lead to good solutions over the whole timespan. The proposed approach can help a company make better decisions which result in lower costs and higher profits.

The results in Table 5 are expanded in order to also consider the time value of money. We assume that each of the nine periods is one month and that the discount rate is 10% p.a.

TABLE 5: *Cutting costs discounted to the first period*

UB \ Period	Per 1	Per 2	Per 3	Per 4	Per 5	Per 6	Per 7	Per 8	Per 9	Total
400	20	22	22	53	19	19	48	0	26	**227**
600	20	22	22	39	19	31	114	17	154	**436**
800	20	20	20	64	0	10	215	19	23	**391**
1000	20	20	20	86	0	19	71	19	36	**290**
1200	20	20	20	131	19	15	84	19	71	**399**
1400	20	20	26	90	19	19	19	19	53	**284**
1600	20	20	26	39	19	19	19	19	19	**200**
1800	20	20	26	78	19	19	63	19	38	**302**
2000	20	20	20	59	0	19	21	19	113	**290**

Table 5 shows the discounted costs with regard to the size of *UB* in each of the nine time periods. The discounted costs do not significantly increase during the additional periods of time which implies that the saturation of stock with partially used pieces is not problematic. The total costs are the sum of discounted costs for all nine periods which are not statistically connected to the size of *UB*.

The idea of Table 5 is not to compare the costs in different periods since it depends on the discount rate. The approach is a very simple application of a well-known technique in finance. Interestingly, the time value of money is almost always completely ignored in cutting stock research and is rarely included in the model.

6. CONCLUSION AND FURTHER RESEARCH

Trim loss minimisation has already yielded near-optimal results and they do not need to be optimised any further. The cutting process therefore needs to be treated as a business process which is incorporated into an entire supply chain. In addition, it needs to be treated as a continuous process which is being executed over consecutive time periods. Its optimisation needs to consider several inputs that come not only from the cutting company but also from its suppliers and buyers. The main contribution of the paper is hence its presentation of the challenges of the cutting stock process and the development and testing of a method that is suitable for cutting in consecutive time periods.

The new approach opens up a new field in CSP research, namely the optimisation of problems over successive time periods rather than just instantaneous optimisation. It is likely that most of the methods developed earlier will need to be tested and (if necessary) modified appropriately to match new business needs.

Treating cutting in a broader view as described above opens several other research questions:

- The inclusion of warehousing costs, which can be included in the objective function. Another possible approach is to develop a simulation model which is used to assess the optimal size of the warehouse while taking different costs into consideration. One such approach has been suggested by Erjavec et al. (2009).
- The optimal size of an order to replenish stocks. While this is a well-researched topic there have been no attempts to assess it in relation to cutting stock. What distinguishes this particular problem from others is the importance of order size.
- The appropriateness of mass customisation with cutting. A case study of costs and benefits should be considered in order to check whether it is useful to use mass customisation closer to the beginning of the supply chain.
- We have shown how and why the greedy behaviour of the algorithm in the first steps can be detrimental to the final solution. Therefore, the idea of Table 5 is to introduce a new way of approaching cutting stock problems. While our method was obviously not specially adapted to this new approach it would be beneficial to develop partly greedy methods for cutting stock which would assign moderate (depending on the discount rate) priority to costs in earlier time periods.

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