Proceedings of the 5th WSEAS International Conference on Applied Computer Science, Hangzhou, China, April 16-18, 2006 (pp601-606)

Mass customization in cutting stock process

PETER TRKMAN, MIRO GRADISAR
Faculty of Economics
University of Ljubljana
Kardeljeva ploscad 17, 1000 Ljubljana
SLOVENIA
; http://www.ef.uni-lj.si

Abstract: In order to achieve mass customization all processes must be structured and executed in a suitable way. The paper shows an approach to cutting stock problem that, in contrary to most available methods, enables continuous cutting and optimization of cutting process over consecutive time periods. It leads to low trim loss and total costs of cutting, while enabling the customization of order lengths and the reusability of material. It presents a solution to a General one-dimensional cutting stock problem, where all stocks can be different.

Key-Words: Mass customization; Agile Manufacturing; Cutting; Optimization; General one-dimensional cutting stock problem; Cutting stock problem with return to stock; Cutting stock over consecutive time periods

1 Introduction

Nowadays, in a fierce competition between companies and supply chains, the concept of continuous improvement is ever-present. The competition is transforming from firm-to-firm competition to competition between supply chains. Mass production with low costs and large series is not longer the dominant response to new challenges.

Supply chains must be structured in such a way to enable quick responses to ever changing customer's needs. Mass customization (MC) seems to be one of the more promising trends of the last decade, as it enables the combination of advantages of mass production and customization.

However MC is not viable without careful design, renovation and usually integration of business processes.

In this paper we focus on the cutting stock process, where a certain number of order lengths has to be cut from available material. This is one of the most important processes for certain companies, specially the producers of raw materials. The process has to be structured and executed in a suitable way to enable MC and enable flexible responses while maintaining operational efficiency. This paper shows a possible approach towards cutting that enables quick response to each individual customer's order while keeping the material and production costs low.

The structure of this paper is as follows: in the next section the main idea and problems of mass customization are presented. Then new solution approach for solving cutting stock problem is proposed, mathematically defined and experimentally tested.

2 Mass customization

MC means producing in volume, but at the same time giving each individual customer something different, according to his needs. It is a process in which all aspects within the organization from people, processes, organizational structures, and technology are geared to provide customers specifically what they need and want [18]. It tries to combine the advantages of both mass production and customization.

MC and Build-to-Order Supply chains are becoming a major objective of many companies as they are migrating from push (sell from stock) to pull (build to customer order) concept [14]. Agile supply chains have to be dynamic, context-specific, flexible across the organization and driven by the customer. New methods, processes and information technology have to be used appropriately. Understanding the characteristics of the product is essential to design a supply chain that meets customer expectations [27].

MC is not possible without proper manufacturing strategies that enable agile manufacturing. Increasing customization requires reorganisation of the activity structures in production and distribution in order to enhance process flexibility [6]. Information technology (especially Internet) is drastically changing the way in which business operate and is increasing the role of MC. The adoption of a new production paradigm is necessary [7].

That can only be achieved by combining skills, technologies, processes and alliances with other partners [2]. The main task is to develop a process which can supply very numerous customer-chosen variations on every order with little lead time or cost penalty [1].

Although MC is an evident trend in practice and a much studied field in theory, very limited research exists in the production operations management literature [20].

Furthermore, the research of MC in connection with the cutting stock problem (CSP) is virtually nonexistent. The main problem in cutting is that the increase in customized orders can cause an increase in trim loss and consequently material costs.

Similar problems than in MC also appear in supply chains, that use continuous replenishment of material, just-in time delivery or similar methods – the supplier has to continuously provide smaller, customized units of material. If cutting of material is necessary for those deliveries, appropriate method is vital for keeping supplier costs low, while fully satisfying each order.

3 Cutting stock problem

Since the seminal work in the 60s [8], [9] cutting stock problem (CSP) has attracted ever increasing attention and several efficient heuristic methods for large problems were developed in recent years [4], [17], [28], [13]. Almost all of those methods focus on instantaneous optimization and try to fulfil different goals with the given data about orders and stock lengths. (see [24] for a detailed review of state-of-the-art cutting methods). They are suitable for batch production and lead to optimal or near-optimal results in such use. However their applicability in MC environment is untested.

Additionally most of existing methods focus on standardized production from one or few available stock lengths. They use pattern-oriented approach to find a good solution. Those methods are mostly suitable for production-to-stock as they produce larger quantities of each order length. The main advantage of patterns usage is namely the reduced time for preparation of cutting plans and cutting machines.

However with quick advances in information technology and automation of production the cutting preparation time and costs are decreasing and the importance of the general cutting problem, where all stock lengths may be different, is increasing [12].

Most methods treat CSP as an isolated process in an isolated time moment with its own objectives. However the role of CSP within the manufacturing strategy (it is defined as a consistent pattern of decision making in the manufacturing function that is linked to the manufacturing strategy [15]) should be considered.

The main goals are low production and trim loss costs over longer time period, while simultaneously enabling continuous production of customized order lengths without advance knowledge of the exact future demand.

As shown in [25] a method, which leads to excellent results in one time period, can lead to highly unsatisfactory results when applied to cutting in consecutive time periods. The main reason is the greedy behaviour of the algorithm that finds a slightly better solution for first periods on the expense of much worse solution for the latter ones. This leads to local instead of global optimization.

Because increases in material and production costs are the most important disadvantage of MC [1], the development of suitable cutting approach is even more vital. The CSP should be structured in such a way to allow agile functioning of the organization [2]. Obviously CSP is only one of the processes in the supply chain – the whole chain should be structured in a suitable way to enable quick response to each customer order [26].

So far only [19] defined an ordered CSP that is suitable for sequential production of orders. However it deals only with known orders in a given time period. This situation is a very simplified picture of reality, because customization is a continuous effort with unknown future orders.

This paper deals with the problem of continuously satisfying customized orders over a longer time period.

3.1. Problem description

The problem is described as follows: in each time period a new customer order has to be fulfilled from available stock at the warehouse. The order consists of a certain number of different order lengths. Exact data about the quantity and lengths of those orders is not known in advance because each customer makes customized orders.

All stock lengths are in general different, however they are not customized (the company does not tailor the length to better fulfil the orders) in order to postpone final product differentiation.

The company seeks a solution to the CSP that will not only optimize or improve its production and decrease trim in the first period, but rather improve the total results over the whole time span. The main goals are low production costs combined with quick production of each order. Therefore several orders cannot be merged into one, as that would cause unnecessary and undesirable delays.

One of the advantages of presented method is the reusability of partly used stock lengths. Unused material from one time period is stored for the next if it is longer than a pre-set upper bound (*UB*). Shorter remainders count as a trim loss. The setting of an *UB* prevents the accumulation of a large number of very short stock lengths that would be useless for future cutting. Depending on the goals of the method, the results can be optimized regarding only trim loss or also other goals (re-usage or inventory costs, priority of orders etc.).

In the problem formulation, special attention is paid to the situation at the end of each period of the problem (i. e. available material left, number of stock lengths in the stock etc). It should be such that good solutions in future time periods are likely. In order to be able to identify the factors, which most influence the likelihood of finding a good solution, extensive testing of solution approaches towards CSP in one time period is necessary [22].

In [11] it was shown that the decrease in the ratio between the average stock length and the average order length has a deteriorating effect on the quality of the final solution as it increases trim loss. It was also shown in [21] that an increase in the number of shorter stock lengths increases the time needed for the solution of a problem with the exact method.

The solution time is especially vital because we need real-time optimization of CSP in each time period, since short lead times are needed for practical implementation of MC – a process capable of quickly adapting to design changes and at the same time, requiring less lead-time, is much needed [16].

In order not to make successive cutting problems harder for successive time periods, it is important to also avoid high numbers of partly cut stock lengths being returned to the warehouse.

Since one order is now much smaller, it is likely to be small enough to be solved exactly within a reasonable time limit. For very large orders heuristic methods can be adapted and used accordingly.

3.2. Problem formulation

The following variables are used in the problem formulation:

s_i - order lengths; $i = 1,,n$.

b_i - required number of pieces of the order length s_i.

d_j - stock lengths; $j = 1,,m$.

x_{ij} - number of pieces of the order length s_i having been cut from the stock length d_j.

UB - upper bound for trim loss.

g_j - shows whether the remainder of stock length is returned to the warehouse (g_j=1, if the remainder of the stock length d_j is returned to the warehouse)

y_j - indicates whether the stock length d_j is used in the cutting plan (y_j = 1, if the stock length d_j is not used in the cutting plan)

c - the costs of a unit of lost material (trim loss)

p_r - the costs of returning one stock length to the warehouse

δ_j - indicates the remainder of the stock length d_j

t_j - indicates the extent of trim loss relating to the stock length d_j. t_j is equal to δ_j for all used stock lengths, except for those that are longer than *UB* and can be returned to the stock and re-used in later cutting stock plans. t_j equals 0 for all unused stock lengths and all stock lengths that are returned to the stock.

The model for each order can now be written as:

(1) $min \sum_{j=1}^{m} \left(t_j * c + g_j * p_r\right)$ (minimize the sum of cutting and return costs)

s. t.

(2) $\sum_{i=1}^{n} (s_i * x_{ij}) + \delta_j = d_j * (1 - y_j) \quad \forall j$ (knapsack constraint)

(3) $\sum_{j=1}^{m} x_{ij} = b_i \quad \forall\ i$ (demand constraint – the number of pieces is fixed)

(4) $UB - \delta_j + UB(g_j - 1) \le 0 \quad \forall j$ (g_j equals 1 only if δ_j is longer than *UB* and $\delta_j * c > p_r$)

(5) $\delta_j - t_j - (g_j + y_j) * (max\, d_j) \le 0 \ \forall j$

(6) $\min d_j \ge UB \ge \min s_i$

$x_{ij} \ge 0$, integer $\quad \forall\, i, j$

$t_j;\ \delta_j \ge 0 \quad \forall j$

$g_j;\ y_j \in \{0,1\} \quad \forall j$

UB can be set between min s_i and min d_j; min s_i is found in practice [10]. In the paper we have also studied the influence of changes in *UB* to the model results.

This problem can be classified to 1/V/D/M/CS type, according to the extended Dyckhoff typology [5], [25].

The model includes costs for returning the stock length to the stock. The reason is twofold: firstly the return of the stock length means certain costs for the company. Secondly with such problem formulation, the solution for each order will return less partly cut stock lengths to the warehouse. In such a way the average length of stock lengths will be higher, thus enabling a higher variety of cutting plans and better possibilities for customization for the future orders.

Namely, it is especially important to ensure that the situation after fulfilment of each order is such to enable likely good solutions in future time periods.

The model does not include cutting preparation costs, as those costs can be neglected in the case of automated production. If necessary, the objective function can be modified to enable the inclusion of those or other relevant costs. For example, we could assume that the transportation to the cutting machine and the preparation for the cutting of one stock length incur some costs (p_t).

The objective function could then be written as

$$\min \sum_{j=1}^{m} \left(t_j * c + g_j * p_r\right) + (m - \sum_{j=1}^{m} y_j) * p_t \qquad (7)$$

where $(m - \sum_{j=1}^{m} y_j)$ denotes the number of stock lengths that are used in the cutting plan. All constraints would remain the same as in the model with return costs above.

3.3. Results

The model was tested with the following assumptions:

- in each of the 9 consecutive time periods a new order has to be fulfilled. Each order consists of customized quantities of optional order lengths. Order lengths vary from 3000 to 6000,
- in each time period a certain quantity of new material arrives to the warehouse in addition to previously unused or partly used and returned material. Available quantity of material enables order satisfaction in each time period. Stock lengths vary from 200 to 400,
- the cost of return of stock length (p_r) is set at 20, cost of unit of material (c) at 2,
- the final result are total costs for the sequence of time periods,
- time limit for solution of each sub-problem is set at 1 minute. It is deliberately low to enable quick solutions and what-if analyses of potential adjustments to customer order,
- the same test data is solved with different *UB* (from 400 to 2000 with the step 200).

The random number generator P-GEN [12] was used for generating the data (stock and order lengths, demand for each order length) for each time period. Each problem was solved with the MPL/CPLEX solver on a personal computer (AMD, 1300 Mhz). The procedure for the experiment is written in Visual Basic for Application (VBA).

The results (cutting costs by period and together) are shown in table 1.

period / *UB*	p1	p2	p3	p4	p5	p6	p7	p8	p9	**sum**
400	20	22	20	54	20	20	50	0	28	**234**
600	20	22	20	40	20	32	120	18	164	**456**
800	20	20	20	66	0	10	226	20	24	**406**
1000	20	20	20	88	0	20	74	20	38	**300**
1200	20	20	20	134	20	16	88	20	76	**414**
1400	20	20	26	92	20	20	20	20	56	**294**
1600	20	20	26	40	20	20	20	20	20	**240**
1800	20	20	26	80	20	20	66	20	40	**312**
2000	20	20	20	60	0	20	22	20	120	**302**

Table 1: Results in consecutive time periods with different upper bounds

All sub-problems are solvable in all time periods, regardless of the *UB* settings and within the time limit. The total cutting costs vary from 234 to 456, while the total trim loss varies from 0,001% to 0,031% of total demand. It can be seen that in this case it is possible to offer customizable order lengths while simultaneously keeping the trim loss costs low.

Additionally, the total costs are low enough to be able to maintain that the described approach is appropriate, although no immediate benchmark testing of the method is possible, because this is the first method proposed for such a problem. Hopefully, new approaches to similar problem solutions will be developed in the future to enable direct benchmark testing.

The fact that there is no statistically significant connection between the *UB* setting and the total costs over the whole optimization time is another interesting observation from the results presented in the Table 1. Pearson correlation coefficient is -0.29, while the significance is 0.45, which means that we cannot claim that changes in *UB* have an effect on the total cutting costs, which is probably due to the dual effect of the increase in the *UB*:

- negative effect for the current time period: the cutting situation is slightly worse because stock remainder has to be longer in order to be returned to the warehouse
- positive effect for future time periods: the average length of the returned stock is increased, which causes less problems in the future time periods.

The results show that both effects approximately nullify each other. The experiment shows that any setting between 400 (the longest order length) and 2000 (approximately 50% of the average stock length) is appropriate.

3.4. Discussion

We showed that with the described modification of the model, local "optimums" lead to good solutions over the whole time-span. The proposed approach can help a company to make better decisions which result in offering customized products at low costs and with increased profits.

Although the presented method was not developed for a particular practical case, it can easily be integrated in the decision support system of an organization. The approach can easily be modified to take company-specific costs into account.

Furthermore the procedure is written in VBA and uses Microsoft Excel as a "user interface" – a tool familiar to most decision makers, both at strategic and operational level. It can be integrated in the decision support system of an organization [3]. Relatively short solution times can also enable the what-if analysis (i. e. the impact of the changes in average inventory level, demand level, frequency of cutting and ratio between c and p_r on the total costs of the process). Additional enhancement could be made to the VBA procedure to develop a more user-friendly interface.

The main advantages of the proposed method are optimization over the long run, its extensibility and user-friendliness, while keeping low costs with customized products. It is especially useful, when material costs are relatively high compared to storage costs, so that it is economically feasible to store partly used stock lengths.

Obviously the presented approach is viable only if organization of production enables both frequent and inexpensive changes in cutting machine setup and storage of material.

Additionally, it should not be forgotten that cutting stock process is only one of the sub-processes of a material replenishment process. Other parts of that process have to be structured accordingly to realize full benefits of a new approach towards cutting.

Future research includes the study of customization possibilities in the case where, due to various problems in supply chain, the available material is insufficient [23].

4 Conclusion

In the paper a new approach for optimization of a CSP problem was shown. Approach towards cutting in consecutive time periods is especially useful if cutting is used for mass customization or is part of a supply chain that uses one of the methods for continuous replenishment of material. It leads both to quick fulfilment of each order and to low total costs of cutting.

References:

[1] Ahlstrom P, Westbrook R, Implications of mass customization for operations management, *International Journal of Operations and Production Management,* Vol. 19, No. 3/4, 1999, pp. 262-275.

[2] Brown S, Bessant J, The manufacturing strategy – capabilities links in mass customization and agile manufacturing – an exploratory study. *International Journal of Operations & Production Management*, Vol. 23, No. 7/8, 2003, pp. 707-730.

[3] Cizman A, Cernetic J, Improving competitiveness in veneers production by a simple-to-use DSS, *European Journal of Operational Research*, Vol. 156, No. 1, pp. 241-260.

[4] Degraeve Z, Peeters M, Optimal integer solutions to industrial cutting-stock problems: Part 2, benchmark results, *INFORMS Journal on Computing*, Vol. 15, No. 1, 2003, pp. 58-81.

[5] Dyckhoff H, A typology of cutting and packing problems, *European Journal of Operational Research*, Vol. 44, No. 2, 1990, pp. 145-159.

[6] Fredriksson P, Gade L, Flexibility and rigidity in customization and build-to-order production, *Industrial Marketing Management,* Vol. 34, No. 7, 2005, pp. 695-705.

[7] Ghiassi M, Spera C, Defining the Internet-based supply chain system for mass customized markets, *Computers & Industrial Engineering*, Vol. 45, No. 1, 2003, pp. 17–41.

[8] Gilmore PC, Gomory RE, A linear programming approach to the cutting stock problem, *Operations Research*, Vol. 9, 1961, pp. 849-859.

[9] Gilmore PC, Gomory RE, A linear programming approach to the cutting stock problem, Part II, *Operations Research*, Vol. 11, 1963, pp. 863-888.

[10] Gradisar M, Jesenko J, Resinovic G, Optimization of roll cutting in clothing industry, *Computers & Operations Research*, Vol. 24, No. 10, 1997, pp. 945-953.

[11] Gradisar M, Resinovic G, Jesenko J, Kljajic M, A sequential heuristic procedure for one-dimensional cutting. *European Journal of Operational Research*, Vol. 114, No. 3, 1999, pp. 557-568.

[12] Gradisar M, Resinovic G, Kljajic M, Evaluation of algorithms for one-dimensional cutting, *Computers & Operations Research*, Vol. 29 No. 9, 2002, pp. 1207-1220.

[13] Gradisar M, Trkman P, A combined approach to the solution to the general one-dimensional cutting stock problem, *Computers & Operations Research,* Vol. 32, No. 7, 2005, pp. 1793-1807.

[14] Gunasekaran A, Ngai E, Information systems in supply chain integration and management, *European Journal of Operational Research*, Vol. 159, No. 2, 2004, pp. 269–295.

[15] Hayes RH, Wheelwright SC, *Restoring Our Competitive Edge, Competing Through Manufacturing*, John Wiley & Sons, 1985.

[16] Kelkar A, Nagi R, Koc B, Geometric algorithms for rapidly reconfigurable mold manufacturing of free-form objects, *Computer-Aided Design*, Vol. 37, No. 1, pp. 1-16.

[17] Menon S, Schrage L, Order allocation for stock cutting in the paper industry, *Operations Research,* Vol. 50, No. 2, 2002, pp. 324-332.

[18] Pine B, *Mass customization: the new frontier in business competition,* Harvard University Press, 1993.

[19] Ragsdale C, Zobel C, The Ordered Cutting Stock Problem, *Decision Sciences*, Vol. 35, No. 1, 2004, pp. 83-100.

[20] Selladurai RS, Mass customization in operations management: oxymoron or reality? Omega, Vol. 32, No. 4, pp. 295-300.

[21] Trkman P, Gradisar M, Choice of method for General One-Dimensional Cutting Stock Problem, *Advances in simulation, systems*

theory and systems engineering, (Electrical and computer engineering series), WSEAS Press, 2002, pp. 17-21

[22] Trkman P, Gradisar M, A comparison between exact and approximate method for solution of general one-dimensional cutting stock problem, *Informatica*, Vol. 27, No. 4, 2003, pp. 495-501.

[23] Trkman P, Gradisar M, Optimization of Cutting Stock Process, *Journal of Mechanical Engineering*, Vol. 49, No. 9, 2003, pp. 469-75.

[24] Trkman P, Gradisar M, The Cutting Stock Problem, *Selected Decision Support Models for Production and Public Policy Problems,* Slovenian Society Informatika, 2005, pp. 135-164.

[25] Trkman P, Gradisar M, Trim loss minimization in continuous cutting stock problem, *Slovenian Informatics Days - conference proceedings*, Portorož, Slovenia, 2005, pp. 448-453 (in Slovenian).

[26] Trkman P, Indihar Stemberger M, Jaklic J, Information Transfer in Supply Chain Management, *Issues in Informing Science and Information Technology Education*, Vol. 2, 2005, pp. 559-573.

[27] Vonderembse M et al., Designing supply chains: Towards theory development, *International Journal of Production Economics*, Vol. 100, No. 2, 2006, pp. 223–238.

[28] Yen C, Wond D, Jang S, Solution of trim-loss problem by an integrated simulated annealing and ordinal optimization approach, *Journal of Intelligent Manufacturing,* Vol. 15 No. 5, pp. 701-709.