Real-time Optimization in Cutting Stock Problems on NC Machines

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Abstract

Due to the orders continued coming from multiple directions at the same time on-line, to stay competitive, such a business has to focus on sustained production at high levels. Operators have to keep the machine running to stay ahead of the pack. Therefore, the continuous stock cutting problem with setup is proposed to minimize the cutting time and pattern changing time to meet the on-line given demand. In this paper, a novel heuristic method is proposed to solve the problem directly by using cutting patterns directly. A major advantage of the proposed method in series on-line production is that the system can adjust the cutting plan according to the floating orders. Examples with multiple items are demonstrated. The results show considerable efficiency and reliability in high-speed cutting of CSP.

Keywords：Cutting stock; Optimization; Heuristics

1. Introduction

The cutting stock problems (CSP) turn up when the large volume of stock material has to be cut into smaller-sized materials to meet the requirements of customer orders. Therefore, cutting stock problems have numerous applications in a wide variety of manufacturing industries [1], from cutting steel and other metals to cutting paper, textiles, furniture [2], wood [3], glass, fiber, shipbuilding and coastal structures [4-6].

Increased manufacturing speeds, while desirable from economic perspectives, can have intense needs on stock supply arrangement and fast computing results to meet high-speed cutting requirement. Fig. 1 shows a high-speed cutting machine on a production line with a stock with maximum conveying speed of 200m/min. For CSP cutting processes, high cutting speeds can induce unpredictable variations in different length, random flaw distribution, holding conditions, and other process bearings. High speed interactions among the machine, cutting blade, and the stock materials may create uncertain conditions that can push the process away from its expected operation, adversely affecting part quality and tool life. Offering increased manufacturing speeds without compromising quality, our method can significantly improve production capabilities and save costs.

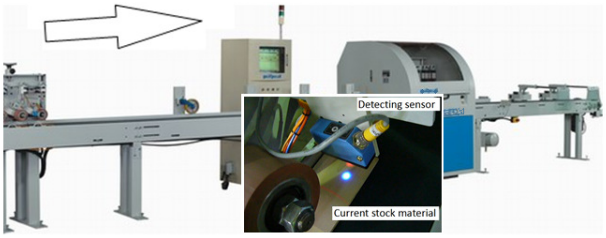

Fig. 1 The real time cutting machine

A cutting stock problem is followed by an optimal stock selection problem. But most of the previous researches focus on only using the off-line optimum algorithms to find the best arrangement of cutting patterns. Thus, it cannot detect the relationship of whole group fraudsters and the execution process should not be real-time. A method is developed and applied using both conventional and the heuristic methods. This method gives nearly optimal solutions in real time. It is applied to both batch-solving and on-line solving of one-dimensional cutting of large-scale production or repetitive manufacturing. A major drawback of modern CNC systems is that the machining parameters, such as feedrate, stock size and number of cut, are still programmed off-line.

Wide treatments in combination of optimum problems appear in many application fields, and various algorithms have been developed so far. However, there are numerous combinatorial optimization problems for which no polynomial time algorithm to find an optimal solution, those problems known as NP-hard [7-8].

For an understanding classification of cutting stock problems, it is referred to Dyckhoff [9] and Wäscher et al. [10]. Dyckhoff made a general description and classification of cutting stock problems prior to 1990. Wäscher et al. made another overview in the same field from 1995 to 2004. Gilmore and Gomory [11] were the first who attempted to solve the one-dimensional cutting stock problem by analytical method.

Holthaus [12] proposed the decomposition approaches based on the classical column-generation technique for solving the integer one-dimensional cutting stock problem with different types of standard lengths. Belov and Scheithauer [13] presented on an algorithm for one-dimensional nesting problem where branching is applied to Gilmore-Gomory formulation. Dikili et al. [14] introduced a successive elimination method to solve one-dimensional cutting-stock problem where cutting plans are achieved directly without the need to establish a mathematical model. The main objective of the method is to reach the optimal integer solution while minimizing the number of different patterns contained in a solution. Valério de Carvalho et al. [15], Degraeve and Peeters [16], Hajizadeh and Lee as well as Alves and Valério de Carvalho [17] all proposed approaches to finding optimal integer solutions to the one-dimensional cutting stock problem. Poldi and Arenales [18] compared different types of rounding heuristics to convert a fractional solution into a feasible integer solution for a slightly modified problem with limited supply of different lengths of stock material.

Johnston and Sadinlija [19] developed a new model for one-dimensional nesting problems that does not require prespecification of cutting patterns. The cutting stock problem in its classic form only considers how large items can be cut into smaller ones in order to meet demand. Additional considerations such as order allocation between parallel machines [20] and a multi-period approach where waste material longer than a given threshold can be returned to the warehouse and used later [21] have also been considered. These problems are therefore much more difficult to solve those cutting stock problems where the sequencing of patterns is arbitrary.

More recently, Yanasse [22] considered sequencing in order to create a cutting plan where the maximum number of open stacks is limited. Dikili et al. [6] proposed an approach to achieve results using cutting patterns directly whereas analytical methods first need to establish a mathematical model. While obtaining ideal solutions of the analytical methods, the new approach limits the wastage to a minimum number of stock materials. Ragsdale et al. [20] proposed a genetic algorithm for the ordered CSP, and more recently Alves and Valério de Carvalho [7] proposed an exact algorithm for the same problem. Their focus is a reduction of in-process inventory levels and material handling activities and their approach only considers the sequencing of complete orders, as opposed to individual cutting patterns. Erajvee et al. [23] presented a methodology for evaluation CS process renovation benefits.

The rest of this paper is organized as follows. The problem is described in the next section. In section 3, we discuss a method for the model and the objectives have to be considered and minimized. A case is introduced to present the new heuristic method with different numerical experiments in section 4. Finally, the conclusions are given in section 5.

2. Problem statement

Traditionally, it is typical to minimize the trim loss in different approaches. The aim of CSP is to cut an object made of material that can be a fast feeding wood, pipe, or wire, etc., to fulfill customer orders. In a cutting problem there are two groups of basic data, whose elements define geometric sizes in one or more dimensions. The material is referred to as the stock of large objects and the list of orders as so-called small items. If there is more than one stock length to be cut to satisfy the demands, the problem is called a multiple stock length CSP. In this paper, we focus on CSPs with multiple stock lengths.

Dyckhoff [9] proposed that cutting problems can be classified using four characteristics. There are dimensionality, kind of assignment, assortment of large objects and assortment of small items. The item-oriented approach is characterized by individual treatment of all items to be cut. In the pattern-oriented approach, order lengths are combined into cutting patterns at first. Follow a succeeding step, the frequencies that are necessary to satisfy the demands will be determined. To solve 1D-CSP in this paper, we need the item-oriented method because all stock lengths can be different. There are two choices to be implemented, exact methods (branch and bound, dynamic programming) or approximation algorithms in the form of Sequential Heuristic Procedure (SHP). SHP seems to be better regarding robustness and potential usefulness in a wide range of cases. Time complexity of SHP can be much lower. Creating a cutting plan for an extensive order takes only a few second on a personal computer. If some exact method should be used, this problem would become intractable.

The majority of the existing research papers focus on standard one-dimensional cutting problem where a single order in a single time has to be fulfilled with a fixed amount of material in stock. The objective of this study is to develop a more feasible method to address one-dimensional nesting problem when multiple sized stock materials are going to be provided during manufacturing process. A concept of placement factor is introduced which avoids to create each two adjacent items are too small due to the holding equipment for each cutting pattern when different sized stock materials are used. The approach presented in this study which incorporates different sized stock materials along with single stock materials, allows the systematic examination of the CSP. Moreover, when single stock material is used, it produces more sensitive and economical results. The conventional model for the objective of minimizing the total cost C to satisfy the orders can be formulated as follows:

$$\min \quad C = \sum_{j=1}^{m} f(W_j, z_j) \qquad (1)$$

where $f(W_j, z_j)$ is a function of W_j and z_j

$$W_j = L_j - \sum_{i=1}^{n} x_{ij} l_i, \quad j = 1,\ldots,m$$

$$z_j = \begin{cases} 1 & \text{if } w_j > 0, \\ 0 & \text{otherwise}, \end{cases} \quad j = 1,\ldots,m \qquad (2)$$

$$\text{Subject to } \sum_{j=1}^{m} x_{ij} = N_i \quad i = 1,\ldots,n \qquad (3)$$

where w_j is the wastage (trim loss) of the jth stock, z_j is the jth stock with wastage, n is the number of different requested items, m is the total number of stocks cut, L_j is the length of the jth stock, x_{ij} is the number of the ith requested item in the jth stock, l_i is the length of the ith requested item, and N_i is the total number of the ith requested item.

3. Solution procedure

As shown in Fig. 2, the problem we discussed in this paper is known as a cutting stock problem with on-line stock sizes detecting, as shown in Fig. 3. Not only the length could be different, but also there could be three various grades of stock material can be chosen for their appropriate quality, normal-grade, medium-grade and high grade. Usually the stock materials are supplied sufficiently with various demands for each item irregularly. The stock materials are fed into the cutting machine with one cutting blade. The tool cuts the current stock with high cutting speed. In order to cut the stock with premium pattern in a very short cutting period after detecting the current stock size, the computing time must less than 0.1 second with the feeding speed 10m/s. According to the application's needs, the proposed procedure is implemented by both conventional and heuristic methods described as follows.

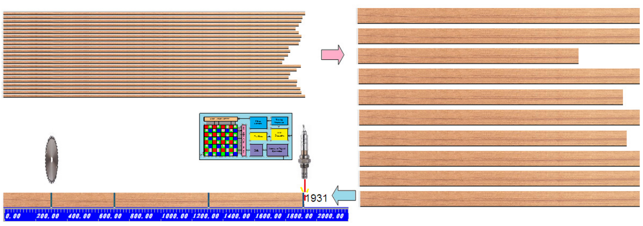

Fig. 2 An illustration of the on-line CSP process

Step 1: n different sized parts demand quantity and grading (L_i, D_i, G_i) are given first.

Step 2: Sort n different sized items according to descending size，

for $k = 1 \sim (n-1)$， $IL_k \geq IL_{k+1}$

Set of the parts is

$$R = \{(L_1, D_1, G_1),\ldots,(L_i, D_i, G_i),\ldots,(L_n D_n, G_n)\} \qquad (4)$$

Step 3: Detect the length and grade of the current stock material S_j.

Step 4: Confirm m different sized stock material of length (to the current stock, m=j).

Step 5: When the combination of cutting patterns are prepared, the ones that exceed the current stock length are already eliminated.

Step 6: Set up the current cutting pattern by evaluating the cost function C while considering the demand quantity, adjacent sizes and grading.

Step 7: Record the wastage W_j.

Step 8: Sort the potential cutting patterns with the maximum value.

Step 9: Maximize the placement factor P_i once the maximum value are equal in step 6. For the current cutting, discriminate the placement factor while considering the automatic feeding and transporting handling.

Step 10: Store the best cutting pattern from all the possible cutting patterns prepared for the current stock materials while considering the demand quantities, wastage and priority (if necessary).

Step 11: Terminate the process if the halting criterion is satisfied, otherwise, go to step 5.

In this case, values of wastage W_j, cost function C_j and placement factor P_j can be calculated using the following relationship.

$$W_j = L_j - \sum_{i=1}^{n} x_{ij} l_i \qquad (5)$$

$$C_j = \sum_{i=1}^{n} x_{ij} l_i w_i \qquad (6)$$

$$\text{Subject to } \sum_{i=1}^{n} x_{ij} l_i + (Nc_j - 1) w_c \leq L_j \qquad (7)$$

where Nc_j is the number of cutting times in the jth stock, w_i is the priority weight of the ith requested item, and w_c is the width of cutting blade.

4. Computational results

Typical cases for 1D-CSP are presented here which use four and more different sizes stock materials, respectively. An example is given below and the complete data for these problems is given latter.

Eight types of items will be cut from different sizes stock material with unknown lengths detected on-line. The dimensions and demand quantities of the parts are given as show in Table 1. The initial condition for gain weight of each item is 1. Suppose the stock materials are supplied sufficiently and the current cutting pattern on-line is to be computed.

In order to obtain the on-line cutting plan for the given problem, the first step should be evaluating the maximum amount of stock materials according to the item specifications and demand quantities to fulfill the continued orders. First, all cutting conditions will be determined for each stock material on-line while taking features of the parts into consideration. Value, wastage and placement factor are calculated for the current cutting pattern. When the current stock size is determined, the demand quantities are considered which reduce the wastage of trim loss. The algorithm exploits the fact that the placement factor can be chosen independently; it chooses a variable ordering that often yields very good prioritized solutions. However, there could be several solutions to the problem. The largest placement factor yields the first solution.

Table 1 Definition of the items.

i	L_i	D_i	w_i
1	200	800	1
2	300	700	1
3	400	600	1
4	450	500	1
5	500	400	1
6	550	300	1
7	600	200	1
8	650	100	1

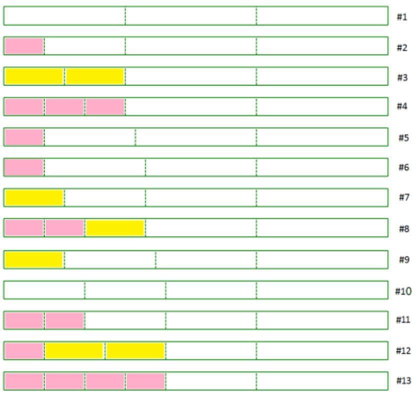

Fig. 3 Pattern layouts of the thirteen possible solutions

In this case, the first result obtained from possible cutting patterns formed for the current stock material are the ones with the largest usage rate where stock material with length $L_j = 1931$ is to be used and nine cutting patterns will be considered. Due to the usage rate are equal, placement factor plays a crucial role to choose the best solution. In this case, after the first heuristic combination process, 13 supreme possible solutions have been brought out from 71 possible solutions by a rule of the largest part included, as shown in Table 2 and Fig. 3. The placement factors of the case in Table 2 are calculated by Eq. 8. The placement factor to be maximized is defined as

$$\frac{\sum_{i=1}^{n}(\sum_{1}^{x_{ij}} i^2)}{N_c} \qquad (8)$$

where x_{ij} denotes the number of the ith item in the jth stock. The placement factors of the case in Table 2 are calculated as:

$$Placement\ Factor\ \#1 = (7^2 + 8^2 + 8^2)/2 = 88.5$$

$$Placement\ Factor\ \#2 = (1^2 + 3^2 + 8^2 + 8^2)/3 = 46$$

$$Placement\ Factor\ \#3 = (2^2 + 2^2 + 8^2 + 8^2)/3 = 45.33$$

All other possible solutions of placement factor are shown in Table 2. The first possible pattern could be chosen based on the rules of the placement factor method. This cutting pattern describes the cutting of one piece of part 7 and two pieces of part 8 from the current stock material, as shown in Fig. 4. The results indicate that the first solution also fit the request of minimum number of cut.

Table 2 Possible cutting pattern for current stock material with length $L_j = 1931$

Possible Solutions	200	300	400	450	500	550	600	650	Usage	No. of Cut	PF
#1	0	0	0	0	0	0	1	2	1900	2	88.5
#2	1	0	1	0	0	0	0	2	1900	3	46
#3	0	2	0	0	0	0	0	2	1900	3	45.33
#4	3	0	0	0	0	0	0	2	1900	4	32.75
#5	1	0	0	1	0	0	1	1	1900	3	43.33
#6	1	0	0	0	1	1	0	1	1900	3	42
#7	0	1	1	0	0	1	0	1	1900	3	37.67
#8	2	1	0	0	0	1	0	1	1900	4	26.5
#9	0	1	0	1	1	0	0	1	1900	3	36.33
#10	0	0	2	1	0	0	0	1	1900	3	32.67
#11	2	0	1	1	0	0	0	1	1900	4	22.75
#12	1	2	0	1	0	0	0	1	1900	4	22.25
#13	4	0	0	1	0	0	0	1	1900	5	16.8

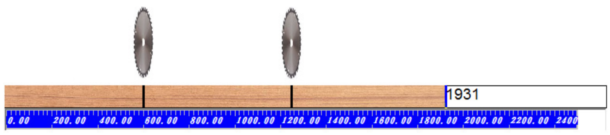

Fig. 4 The final cutting pattern with length $L_j = 1931$

Table 3 The first sixteen possible cutting pattern for the second stock material with length $L_j = 2054$

Possible Solutions	200	300	400	450	500	550	600	650	Usage	No. of Cut	PF
#1	1	0	0	0	1	0	0	2	2000	3	51.33
#2	0	1	1	0	0	0	0	2	2000	3	47
#3	2	1	0	0	0	0	0	2	2000	4	33.5
#4	1	0	0	0	0	1	1	1	2000	3	50
#5	0	1	0	1	0	0	1	1	2000	3	44.33
#6	0	1	0	0	1	1	0	1	2000	3	43
#7	0	0	2	0	0	1	0	1	2000	3	39.33
#8	2	0	1	0	0	1	0	1	2000	4	27.75
#9	1	2	0	0	0	1	0	1	2000	4	27.25
#10	4	0	0	0	0	1	0	1	2000	5	20.8
#11	0	0	1	1	1	0	0	1	2000	3	38
#12	2	0	0	1	1	0	0	1	2000	4	26.75
#13	0	0	0	3	0	0	0	1	2000	3	37.33
#14	1	1	1	1	0	0	0	1	2000	4	23.5
#15	0	3	0	1	0	0	0	1	2000	4	23
#16	3	1	0	1	0	0	0	1	2000	5	17.4

All other possible solutions of usage are shown in Table 3. The 9th possible pattern has been chosen based on the rules of the virtual usage method. This cutting pattern describes the cutting of four pieces of part 1 and one piece of part 2 from the current stock material, as shown in Fig.5. The final results are implemented by gain weights as the best solution without placement factor determination. The manufacturing schedule can vary greatly based on the size and gain weight of each item. The volume of each item will increase by following this cutting pattern until reach the demand of each item or change various parameters.

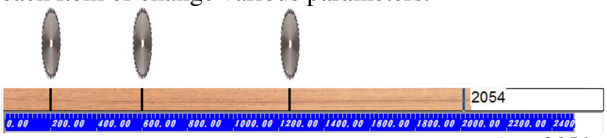

Fig. 5. The final cutting pattern with length $L_j = 2051$

Table 4 Definition of the items with weights.

i	L_i	D_i	w_i
1	200	800	2
2	300	700	1.5
3	400	600	1
4	450	500	1
5	500	400	1
6	550	300	1
7	600	200	1
8	650	100	1

A major advantage of the proposed method in series on-line production is that the system can adjust the cutting plan according to current stock size by real time detecting. Generally speaking, real-time response for stock length from inventory stock size for some items are found in patterns that are more flexible than those that have only one size for that same production. Take example 2 for instance, if the first stock material has been cut with length $L_1 = 1931$. One piece of part 7 and two pieces of part 8 have been produced by the first cutting operation. In order to obtain the on-line cutting plan for the given problem of detecting the next stock material, value, wastage and placement factor are recalculated for the current cutting pattern with length $L_2 = 2054$. When the current stock size is determined, the demand quantities are considered which reduce the wastage of trim loss. Then, cutting patterns are determined according to the renewed size and similarly the solution with the largest usage rate is chosen. The actual usages are subject to equation 7. Due to the usage rate are equal, placement factor plays a crucial role to choose the best solution. In this case, after the first heuristic combination process, 16 supreme possible solutions have been brought out from 89 possible solutions by a rule of the largest part included, as shown in Table 3. The first possible pattern could be chosen based on the rules of the placement factor method. This cutting pattern describes the cutting of one piece of part 2, 5 and two pieces of part 8 from the current stock material, as shown in Fig. 5. The results indicate that the first solution also fit the request of minimum number of cut. After the first heuristic combination process, 13 possible solutions have been brought out to meet the maximum usage rate. The weights of the parts are changing as show in Table 4. Further calculation for the virtual usage with different gain weights of the case in Table. 2 are calculated as:

$$C\ \#1 = 600*1*1+650*1*2 = 1900$$
$$C\ \#2 = 200*2*1+400*1*1+650*1*2 = 2100$$
$$C\ \#3 = 300*1.5*2+650*1*2 = 2200$$
$$C\ \#4 = 200*2*3+650*1*2 = 2500$$
$$C\ \#5 = 200*2*1+450*1*1+600*1*1+650*1*1 = 2100$$
$$C\ \#6 = 200*2*1+500*1*1+550*1*1+650*1*1 = 2100$$
$$C\ \#7 = 300*1.5*1+400*1*1+550*1*1+650*1*1 = 2050$$
$$C\ \#8 = 200*2*2+300*1.5*1+550*1*1+650*1*1 = 2450$$
$$C\ \#9 = 300*1.5*1+450*1*1+500*1*1+650*1*1 = 2050$$
$$C\ \#10 = 400*1*2+450*1*1+650*1*1 = 1900$$
$$C\ \#11 = 200*2*2+400*1*1+450*1*1+650*1*1 = 2300$$
$$C\ \#12 = 200*2*1+300*1.5*2+450*1*1+650*1*1 = 2400$$
$$C\ \#13 = 200*2*4+450*1*1+650*1*1 = 2700$$

The 13th possible pattern has been chosen based on the rules of the virtual usage method. This cutting pattern describes the cutting of four pieces of part 1 and one piece of part 4, 8 from the current stock material. The final results are implemented by gain weights as the best solution without placement factor determination. The manufacturing schedule can vary greatly based on the size and gain weight of each item. The volume of each item will increase by following this cutting pattern until reach the demand of each item or change various parameters.

5. Conclusion

In this paper we have proposed a novel method to cutting stock problem where we seek an optimum solution in dynamic orders without managing stock materials in advance. The results of the testing cases in practice show that using different sized stock materials without limits yield economical and practicable results.

The present method also helps finding the ideal solution for a single type of stock material. Because the stock materials are fed into the cutting machine with the speed of 200m/min, the solution is achieved in 1/10 second. Therefore, the solution has to be completed much faster than ever before. The present method which involves heuristic selection at the initial combination is based on the solution for the single sized stock material developed by Gilmore and Gomory. The solution finding process has been simplified for multiple length stock materials. The creative approximation involves the use of cutting patterns along with placement factor. Whenever the usage rate comes to equal, placement factor is a usage value for any cutting pattern which effectively realizes the cutting patterns in the nesting problem.

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NC 機台線上即時裁斷最佳化

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摘要

由於訂單可持續從多個管道同時及時下單，為保持市場競爭力，企業必須專注在高檔次且可持續生產的模式，製造單位要在產品包裝運送之前都保持機器的運轉。因此連續性切割整備問題被提出來以減少切削和產品樣板變更整備的時間，以滿足線上即時下單的需求。直接由目前使用的產品樣板，本文提出一個新啟發方法來解決這個動態問題。持續性線上生產規劃所提出的方法具備一個重要優點，該系統可以由浮動的訂單動態調整目前的切割計劃的。實例切割證明在高速切削的 CSP 生產中，本方法具備相當大的效率和可靠性。

關鍵字 ： 切料、最佳化、啟發式