The N-Sheet Model in Capacitated Multi-Period Cutting Stock Problem with Pattern Set-Up Cost

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***Abstract*— Cutting Stock Problem (CSP) is a problem to optimize the stock usage with specifics cutting patterns. This research implemented the N-Sheet model in Capacitated Multi-Period Cutting Stock Problem with the pattern set-up cost. This study used the data of the rectangular stocks, which cut to a variety of item sizes. The *Pattern Generation* (PG) algorithm determined the cutting patterns. The PG produced 21 optimal patterns based on the length and 23 optimal patterns based on the width to fulfil customer requirements. And then, we formulated the patterns into the N-Sheet model. The optimal solution from the N-Sheet model in this research were six cutting patterns. We used the 1st, 2nd, 5th, and 19th patterns for cutting based on length, and the 4th and 23rd patterns for cutting based on the width. The solutions of the model were not so optimal because it yielded too many surplus items.**

Keywords—Cutting Stock Problem, Pattern Generation, N-Sheet, Multi-Period, Pattern

I. Introduction

Industry players are always looking for ways to get optimal profits without increasing capital or detrimental consumers. They can optimize raw materials and minimize the remaining cut (trim loss). Wood, paper, glass, steel, marble, and other industries mostly used this method. The problem of setting raw materials in Operation Research (OR) is commonly called the Cutting Stock Problem (CSP), which is cutting the available standard raw materials in specific sizes to minimize the trim loss. According to its dimensions, CSP consists of one-dimensional CSP, two-dimensional CSP, and three-dimensional CSP. Cutting only one side is called a one-dimensional CSP. This study discussed two-dimensional CSP, where the cutting considers the width and length of the raw material. Meanwhile, for three-dimensional CSP, cutting considers the width, length, and height.

Reference [1] said that in general, cutting raw materials consists of cutting a specific set of small objects or commonly referred to as items, from certain more massive groups, called stock sheets. Reference [2] stated that according to its form, CSP is divided into two, namely irregular and regular.

Researchers have developed CSP research from time to time with various problem-solving algorithms starting from pattern formation [2]–[6], model building [7]–[10], and solving methods [11]–[13]. Two-dimensional CSP using the Arc-Flow model with guillotine constraints was formulated by [1]. And then, [14] used the matheuristic approach to solved the Arc-Flow model. In general, CSP research uses the Arc-flow model and other models, such as the N-Sheet model, Dotted Board and others. Another study was conducted by [15] regarding two-dimensional CSP of the guillotine problem by minimizing trim loss. This study's result indicated a modified model to handle specific cases, for example, the correct two-stage guillotine cutting without trimming. Reference [16] proposed two heuristics for the capacitated multi-period CSP with the pattern set-up cost.

Capacitated multi-period CSP is a cutting process with more than one period, where the period is the units of time for completing the work. Furthermore, [17] created a pattern formation program for two-dimensional CSP using a modified Branch and Bound algorithm, but this program still produces many of the same patterns. Reference [6] examined CSP with the Pattern Generation algorithm for one-dimensional problems with pattern setting costs. Reference [18] implemented the Branch and Cut method in the two-dimensional N-Sheet CSP model, wherein this study did not take the pattern set-up cost. They used the N-Sheet model for solving problems with one-dimensional or two-dimensional raw materials. This model can solve a single stock or multiple stock problems, however they used only a single period, not multi-periods.

This study designed the cutting patterns for rectangular and guillotine-shaped items with the pattern set-up cost. The cost included the inventory cost per unit in each period, each item's usage cost and the pattern cost. The search for cutting patterns in this study used the Pattern Generation algorithm. There have been limited studies concerned with capacitated multi-periods CSP. Therefore, this research formulated the

N-sheet model on the Capacitated Multi-Period CSP to minimize the trim loss.

II. Research Method

There are some steps taken in this study. First, we described and classified data. These data included the stock's size, item's length, width measurements, and item's requests. The stocks were rectangular, and there were three types of item's dimension. The data implemented in the Pattern Generation algorithm were sorted, descending from the most extensive to the smallest sized product. The Pattern Generation algorithm processed data to obtain the first stage cutting pattern and the second stage cutting pattern. The N-Sheet model was formulated and solved it using the LINDO 61 program.

III. Result and Discussions

This study used paper raw material data in the form of a rectangle with a length of 3,000 mm and a width of 3,500 mm with three items. Table 1 showed the item's sizes and demand.

Table 1. Item Size and Demand

The i^{th} item	Length	Width	Number of Demand
1	378 mm	200 mm	75 sheets
2	555 mm	496 mm	6 sheets
3	555 mm	755 mm	4 sheets

Table 1 showed the highest demand was 75 sheets, while for the second demand as many as six sheets, and third demand as many as four sheets. There are three items, with 378 mm × 200 mm, 555 mm × 496 mm, and 555 mm × 755 mm dimensions.

The stock with standard width ($w' = 3{,}500$) and standard length ($l' = 3{,}000$) is cut to 3 sizes with a certain width and length, respectively denoted by w_i and l_i where ($i = 1, 2, 3$) and $w_1 > w_2 > w_3$. The cutting pattern of the PG algorithm is needed to meet the demand. A cutting pattern with the minimum trim loss is referred to as a feasible cutting pattern.

We obtained the feasible cutting pattern through a search tree. The tree level represents the required width, arranged in descending order where the largest is at the first level while the smallest size is placed at the tree's last level. The initial vertex of the first level represents the standard width used to generate the pattern. Therefore, a separate search tree is used to create patterns according to each standard width.

The branch of level i in the search tree represents the multiplication of the number of items by the width w_i obtained according to the j^{th} cutting pattern. This multiplication represents the sum of the widths cut from the stock to fill the width w_i. The vertices from the second level to the n^{th} level represent the remaining width after fulfilling the specified cut from the previous $i-1$ branch. The final vertex of the search tree shows the remaining reductions resulting from the different cutting patterns. The search tree is built from top to bottom, then left to right.

We generate the cutting pattern by applying PG algorithm [2] to the data in Table 1. The steps of the PG algorithms are as follows [2]:

1. Ordering the width w_i ($i = 1, 2, 3$) in descending order. So, we have $w_1 = 555$ mm, $w_2 = 555$ mm, and $w_3 = 378$ mm.
2. Use Eq. 1 to fill the first column. ($j = 1$)
   $$a_{i1} = \left\lfloor \frac{w' - \sum_{z=1}^{i-1} a_{z1} w_z}{w_i} \right\rfloor, i = 1, 2, 3 \qquad (1)$$
3. Use Eq. (2) to find the trim loss.
   $$c_j = w' - \sum_{i=1}^{3} a_{ij} w_i \qquad (2)$$
4. Set level index (row index) i to $n-1$.
5. Check level of vertex, eg. vertex (i, j). If the vertex equals to zero $(a_{ij} = 0)$, go to Step 7. If not generate new column $j = j + 1$ with these elements:
   a. $a_{zj} = a_{z(j-1)}$ ($z = 1, 2, \ldots, i-1$) to fill the preceeding vertex (i, j).
   b. $a_{ij} = a_{i(j-1)} - 1$ to fill the vertex (i, j).
   c. Fill the remaining from vertex-j using Eq. (3).
   $$a_{ij} = \left\lfloor \frac{w' - \sum_{z=1}^{i-1} a_z w_z}{w_i} \right\rfloor \qquad (3)$$
6. Use Eq. (2) to find the trim loss from the j^{th} pattern. Go back to Step 4.
7. Set $i = i - 1$. If $i > 0$, go to Step 5. Otherwise, stop.

By implementing the PG algorithm and the data in Table 1, we got 21 cutting patterns based on the length shown in Fig. 1 and 2. We must read the search tree in Fig. 1 from top to bottom and continue from left to right. From Fig. 1, we can see that the first level is 3,000. It means that the length of the stock is 3,000 mm. After that, we took the second level of the tree from the top. If we used the 3,000 mm of the stock to cut the item with a length of 555 mm, we could get five pieces of 555 mm. The remaining stock is 225 mm. From 225 mm of the remaining, we continue to the third level of the search tree. 225 mm of the remaining can not use any more to cut the second item of 555 mm, so the number of cutting is 0. In the fourth level of the search tree, we use 225 mm of the remaining paper to cut the third item with 378 mm. Because the remaining stock is smaller than the item, we can not use it to cut for the third item, and the number of cuts in the fourth level becomes zero. We can see the trim loss in the last vertex at the tree's bottom. The first pattern based on the length is five pieces of 555 mm with 225 mm of trim loss. The second pattern is four pieces of 555 mm and a piece of 555 mm with 225 mm of trim loss. The third pattern is four pieces of 555 mm and two pieces of 378 mm with 24 mm of trim loss. The patterns continue until the 21^{th} pattern. Fig. 2 is a continuation of Fig. 1. For details, the cutting patterns based on the length as shown in Fig. 1 and Fig. 2 can be seen in Table 2.

On the other hand, by implementing the PG algorithm to the data in Table 1, we got 23 cutting patterns based on the width. These patterns can be seen in Fig. 3 and Fig. 4. We also must read the search tree in Fig. 3 from top to bottom and continue from left to right. From Fig. 3, we can see that the first level is 3,500. It means that the length of the stock is 3,500 mm. After that, we took the second level of the tree from the top. If we used the 3,500 mm of the stock to cut the item with a length of 755 mm, we could get four pieces of 755 mm.

The remaining stock is 48 mm. From 48 mm of the remaining, we continue to the third level of the search tree. 48 mm of the remaining can not use any more to cut the second item of 496 mm, so the number of cutting is 0. In the fourth level of the search tree, we use 48 mm of the remaining paper to cut the third item with 200 mm. In this last level, we get 2 pieces of 200 mm. The trim loss is in the last vertex at the tree's bottom. The first pattern based on the width is four pieces of 755 mm and two pieces of 200 mm, with 80 mm of trim loss. The second pattern is three pieces of 755 mm, two pieces of 496 mm, and a piece of 200 mm with 43 mm of trim loss. The third pattern is three pieces of 755 mm, a piece of 496 mm, and three pieces of 200 mm with 139 mm of trim loss. The patterns continue until the 23^{rd} pattern. Fig. 3 is a continuation of Fig 4. For details, the cutting patterns based on the width as shown in Fig. 3 and Fig. 4 can be seen in Table 3.

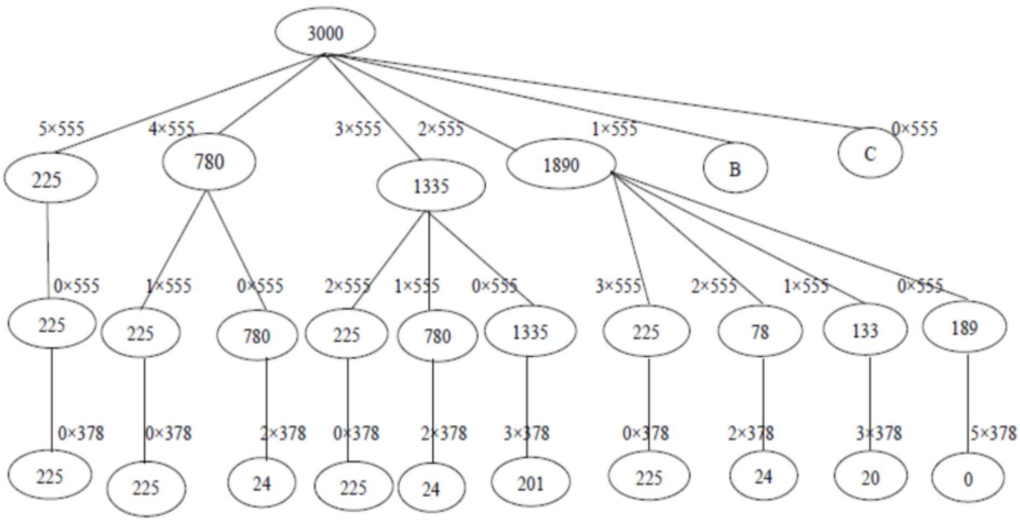

Figure 1. The Tree of Cutting Patterns Based on The Length Part 1

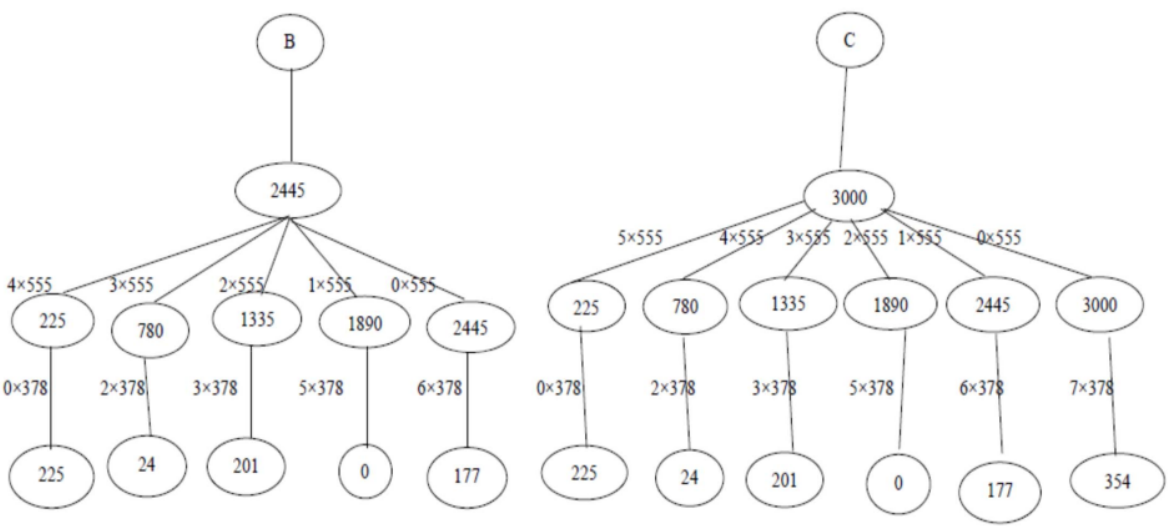

Figure 2. The Tree of Cutting Patterns Based on The Length Part 2

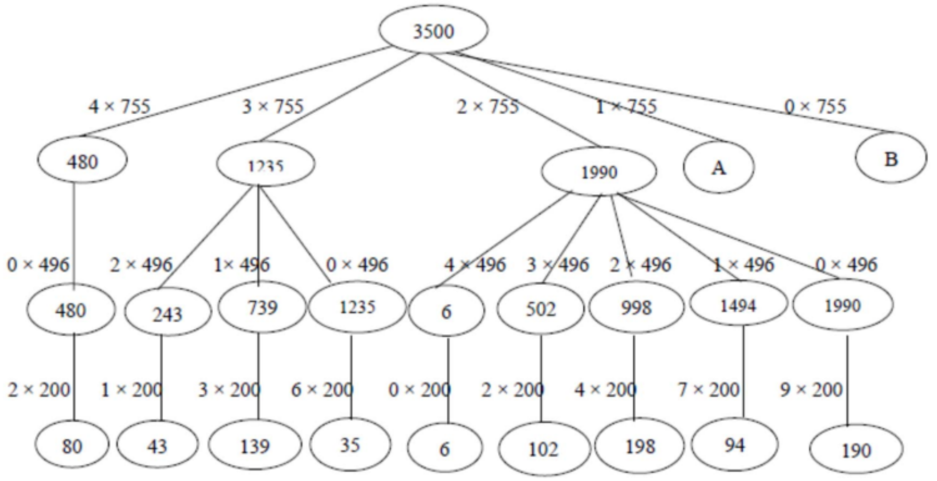

Figure 3. The Tree of Cutting Patterns Based on The Width Part 1

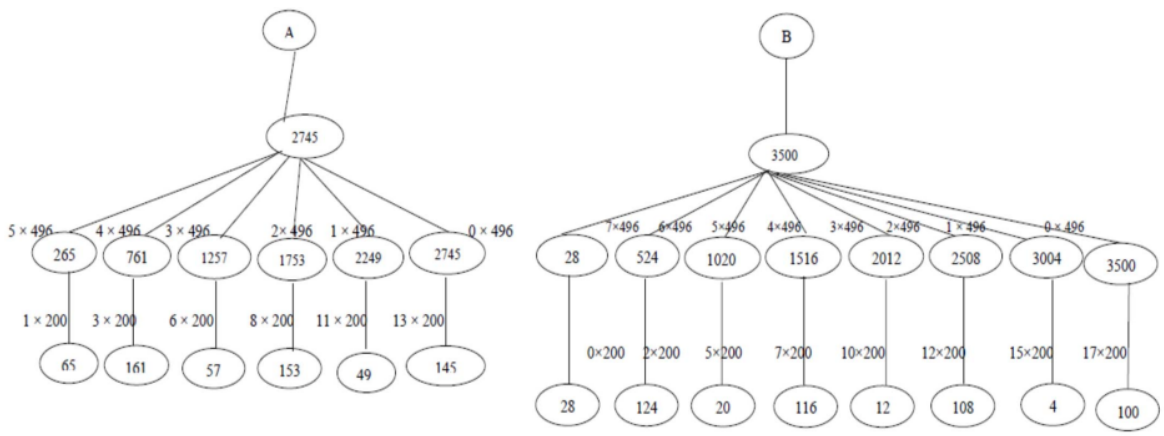

Figure 4. The Tree of Cutting Patterns Based on The Width Part 2

From Table 2, if we use the first pattern, we can get five pieces of items with length 555 mm and 225 mm of trim loss, and so on until the 21st pattern. From Table 3, if we use the first pattern, we can get four pieces of items with width 755 mm, two pieces of items with width 200 mm, and 80 mm of trim loss. All of the patterns from Table 2 and 3 were formulated to the N-Sheet model. The objective function of the N-Sheet model is to minimize the trim loss in order to obtain an optimal cutting pattern.

The N-Sheet model for the cutting patterns in Table 2 and Table 3 can be seen in Model (4)-(8).

x_p is the number of p pattern which cut based on the length.
y_p is the number of p pattern which cut based on the width.
l_{ij} is the number of the i^{th} item which cut according to the j^{th} pattern.

Minimize

$$Z = \sum_{t=1}^{T}\left(\sum_{i=1}^{n} h_i I_{it} + \sum_{p=1}^{p^{max}} (pC + \beta)x_p\right) + \sum_{t=1}^{T}\left(\sum_{i=1}^{n} h_i I_{it} + \sum_{p=1}^{p^{max}} (pC + \beta)y_p\right) \quad (4)$$

Subject to :

$$\sum_{i=1}^{p^{max}} l_{ij}x_p \leq I_i, i = 1, \dots, p^{max} \quad (5)$$

$$\sum_{j=1}^{p^{max}} l_{ij}y_p \leq I_i, j = 1, \dots, p^{max} \quad (6)$$

$$\sum_{i=1}^{p^{max}} x_p = \mathbb{N}, i = 1, \dots, p^{max} \quad (7)$$

$$\sum_{j=1}^{p^{max}} y_p = \mathbb{N}, \ j = 1, \dots, p^{max} \quad (8)$$

n is the number of item.
T is the number of period, $T = 2$
h_i is the inventory cost per unit per period.
L is the length of stock, $L = 3{,}500$
C is the unit cost, $C = 3{,}500$

I_{it} is the inventory number of the i^{th} item in the t^{th} period.
p is the number of pattern.
t is the period.
β is the pattern set up cost, $\beta = 0.01\ L$
$\mathbb{N}$ is the positive integer number
p^{max} is the maximum number of patterns

By using the data in Table 1 with the variables and parameters that had explained before, the N-Sheet model can be seen in Model (9).

TABLE 2. THE CUTTING PATTERNS BASED ON THE LENGTH

The j^{th} pattern	The Number of Items			Trim loss (mm)
	555 mm	555 mm	378 mm	
1	5	0	0	225
2	4	1	0	225
3	4	0	2	24
4	3	2	0	225
5	3	1	2	24
6	3	0	3	201
7	2	3	0	225
8	2	2	2	24
9	2	1	3	201
10	2	0	5	0
11	1	4	0	225
12	1	3	2	24
13	1	2	3	201
14	1	1	5	0
15	1	0	6	177
16	0	5	0	225
17	0	4	2	24
18	0	3	3	201
19	0	2	5	0
20	0	1	6	177
21	0	0	7	354

TABLE 3. THE CUTTING PATTERNS BASED ON THE WIDTH

The j^{th} pattern	The Number of Items			Trim loss (mm)
	755 mm	496 mm	200 mm	
1	4	0	2	80
2	3	2	1	43
3	3	1	3	139
4	3	0	6	35
5	2	4	0	6
6	2	3	2	102
7	2	2	4	198
8	2	1	7	94
9	2	0	9	190
10	1	5	1	65
11	1	4	3	161
12	1	3	6	57
13	1	2	8	153
14	1	1	11	49
15	1	0	13	145
16	0	7	0	28
17	0	6	2	124
18	0	5	5	20
19	0	4	7	116
20	0	3	10	12
21	0	2	12	108
22	0	1	15	4
23	0	0	17	100

Minimize

$$Z = 13{,}1l_{11} + 13{,}1l_{12} + 10{,}51l_{21} + 10{,}51l_{22} + 5{,}78l_{31} + 5{,}78l_{32} + 3535x_1 + 7035x_2 + 10535x_3 + 14035x_4 + 17535x_5 + 21035x_6 + 24535x_7 + 28035x_8 + 31535x_9 + 35035x_{10} + 38535x_{11} + 42035x_{12} + 45535x_{13} + 49035x_{14} + 52535x_{15} + 56035x_{16} + 59535x_{17} + 63035x_{18} + 66535x_{19} + 70035x_{20} + 73535x_{21} + 3535y_1 + 7035y_2 + 10535y_3 + 14035y_4 + 17535y_5 + 21035y_6 + 24535y_7 + 28035y_8 + 31535y_9 + 35035y_{10} + 38535y_{11} + 42035y_{12} + 45535y_{13} + 49035y_{14} + 52535y_{15} + 56035y_{16} + 59535y_{17} + 63035y_{18} + 66535y_{19} + 70035y_{20} + 73535y_{21} + 77035y_{22} + 80535y_{23}$$

Subject to : (9)

$$7x_1 + 6x_2 + 5x_3 + 3x_4 + 2x_5 + 6x_7 + 5x_8 + 3x_9 + 2x_{10} + 5x_{12} + 3x_{13} + 2x_{14} + 3x_{16} + 2x_{17} + 2x_{19} \geq 75$$
$$x_2 + 2x_3 + 3x_4 + 4x_5 + 5x_6 + x_8 + 2x_9 + 3x_{10} + 4x_{11} + x_{13} + 2x_{14} + 3x_{15} + x_{17} + 2x_{18} + x_{20} \geq 6$$
$$x_7 + x_8 + x_9 + x_{10} + x_{11} + 2x_{12} + 2x_{13} + 2x_{14} + 2x_{15} + 3x_{16} + 3x_{17} + 3x_{18} + 4x_{19} + 4x_{20} + 5x_{21} \geq 4$$
$$17y_1 + 15y_2 + 12y_3 + 10y_4 + 7y_5 + 5y_6 + 2y_7 + 13y_9 + 11y_{10} + 8y_{11} + 6y_{12} + 3y_{13} + y_{14} + 9y_{15} + 7y_{16} + 4y_{17} + 2y_{18} + 6y_{20} + 3y_{21} + y_{22} + 2y_{23} \geq 75$$
$$y_2 + 2y_3 + 3y_4 + 4y_5 + 5y_6 + 6y_7 + 7y_8 + y_{10} + 2y_{11} + 3y_{12} + 4y_{13} + 5y_{14} + y_{16} + 2y_{17} + 3y_{18} + 4y_{19} + y_{21} + 2y_{22} \geq 6$$
$$y_9 + y_{10} + y_{11} + y_{12} + y_{13} + y_{14} + 2y_{15} + 2y_{16} + 2y_{17} + 2y_{18} + 2y_{19} + 3y_{20} + 3y_{21} + 3y_{22} + 4y_{23} \geq 4$$
$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} \geq 1$$
$$y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8 + y_9 + y_{10} + y_{11} + y_{12} + y_{13} + y_{14} + y_{15} + y_{16} + y_{17} + y_{18} + y_{19} + y_{20} + y_{21} + y_{22} + y_{23} \geq 1$$
$$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, , x_{21} \geq 0$$
$$y_1, y_2, y_3, y_4, y_5, y_6, y_7, y_8, y_9, y_{10}, y_{11}, y_{12}, y_{13}, y_{14}, y_{15}, y_{16}, y_{17}, y_{18}, y_{19}, y_{20}, y_{21}, y_{22}, y_{23}, I_{11}, I_{12}, I_{21}, I_{22}, I_{31}, I_{32} \geq 0$$

x_i is the number of the i^{th} pattern which cut based on the length, $i = 1,2,3,\ldots,21$.
y_j is the number of the j^{th} pattern which cut based on the width, $j = 1,2,3,\ldots,23$.

By using the LINDO 61, the optimal solution of Model (9) is $Z = 12$, $x_1 = 9, x_2 = 2$, $x_5 = 1$, $x_{19} = 1, y_4 = 2$, $y_{23} = 28$. Based on the optimal solution obtained, we have some of the results, as shown below.

$Z = 12$ means that we must use 12 pieces of stocks with dimension 3,000 mm × 3,500 mm,

$x_1 = 9$ means that it is possible to use the 1st cutting pattern nine times,
$x_2 = 2$ means that we use the 2nd cutting pattern two times,
$x_5 = 1$ means that we use the 5th cutting pattern one time,
$x_{19} = 1$ means that we use the 19th cutting pattern one time,
The value of x_1, x_2, x_5, and x_{19} means that the 1st, 2nd, 5th and 19th are cutting patterns based on the length in the first stage. Also the value of y_4 and y_{23} means that the 4th and 23rd are cutting patterns based on the width.

y_4 =2 means that the 4th cutting pattern is cut two times, and y_{23} = 28 means that the 23rd cutting pattern is cut 28 times based on the width. From the results, there are still many cutting patterns chosen. And if we use the optimal patterns, there will be many surplus for the first item.

Compare to the research by [18], Model (9) in this research are still not useful enough in solving the problem with data in Table 1, because of the surplus items.

IV. CONCLUSIONS

Based on the results and discussion, the N-Sheet model can be used for single stock CSP where it can include the cost component of pattern set. The pattern set-up cost consists of the cost of the inventory per unit in each period, the cost of using each item and the cost of determining the pattern. These costs have been determined from the beginning of the cutting pattern. The optimal solution obtained shows that there is a great deal of surplus for the first item. The solution shows that the N-Sheet CSP Capacitated Multi-Period model is not useful enough in solving problems in the data of Table 1.

For further research, the Cutting Stock Problem model's more extensions are critically essential to improve than previous models. We suggest computational tests for further study.

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