An Application of Cutting-Stock Problem in Green Manufacturing: A Case Study of Wooden Pallet Industry

P Wattanasiriseth* and A Krairit
Engineering and Technology Management Program, Department of Industrial Engineering, Faculty of Engineering at Sriracha, Kasetsart University, Chonburi, Thailand

Corresponding author *: paveepat@hotmail.com

Abstract. The cutting-stock problem is used to minimize the impact of wasting material during the stock cutting process. The linear programming model is developed and implemented on Microsoft Excel to solve for the optimal cutting plan with the criteria of minimizing material waste. The case study of pine wood stock cutting in wooden pallet industry demonstrates the benefit of using the approach in terms of reducing production cost and carbon emission. The results show that waste can be reduced up to 70.86% resulting in a cost reduction of 977,352 Baht/year. The amount of carbon dioxide equivalent emitted from the life cycle of pine wood is reduced by 22,713 kg CO₂-e/year or approximately 5.32% reduction.

1. Introduction
Pine wood is one of the major raw materials in wooden pallet industry of Thailand regardless of its low supply in Thailand. Approximately 60% of wooden pallets produced in Thailand are made of imported pine wood from various sources around the world, mostly America, Finland, Sweden, Brazil, Russia and New Zealand. A cheaper local wood supply such as parawood is the main alternative, however, pine wood pallet is still preferred by customers around the globe forcing Thai wooden pallet industry to manufacture the wooden pallet from the more expensive source of raw material such pine wood.

Beside the incurred cost from importing of pine wood and the risk of currency exchange fluctuation. The greenhouse gas emission related to harvesting, sawmilling, shipping, and manufacturing of pine wood product is another major concern. With the growth of Thailand manufacturing industry, more wooden pallets will be required for carrying products and shipping them to the whole world. One solution to the problem of increasing demand for imported pine wood for wooden pallets industry is to reduce the amount of pine wood wasted during the production process due to poor production management and inadequate manufacturing technology. Minimizing the waste pine wood could result in a saving of production cost and greenhouse gas emissions which is an approach toward achieving green manufacturing.

Based on the observation in Thailand wooden pallet industry, most of pine wood waste are generated during the stock cutting process. The imported pine wood with standard sizes is cut down to the required sizes leaving lots of unusable remaining waste (off-cuts). The pine wood waste is accounted for the cost of pallet and the amount of greenhouse gas emitted to the world. This problem can be easily minimized through improving production management such as optimizing the cutting plan of pine wood based on the production demand.
Cutting-Stock Problem (CSP) is wildly used to solve this type of problem and it is generally used in lumber and steel industries [1]. This optimization technique can select the optimal cutting pattern to minimize the material waste while meeting the production demand. However, most wooden pallet manufacturers are small and medium enterprises (SMEs) who is lacking of know-how and capital to invest in such optimization system. Thus, they are likely to rely on a simple but inefficient way of stock-cutting resulting in high amount of waste, high production cost and high greenhouse gas emissions. Therefore, in this research, the aim is to develop the Microsoft Excel-based optimization system for solving one dimensional cutting-stock problem with the objective of minimizing material waste. The case study of cutting pine wood in wooden pallet manufacturing is used for an implementation and analysis of both cost and carbon emission.

2. Literature Review

2.1. Green Manufacturing

There has been a focus on the impact of organizations and manufacturing on the overall environment. Stakeholders including customers, shareholders, board members, and employees are asking or requiring organizations to be more environmentally responsible with respect to their products and processes. The reasons for these demands include regulatory requirements, product stewardship, enhanced public image, potential to expand customer base, and potential competitive advantages. [2] Therefore, the term “green manufacturing” was invented to emphasize the focus of manufacturers toward this environmental aspect.

The term “green” manufacturing can be looked at in two ways: the manufacturing of “green” products, particularly those used in renewable energy systems and clean technology equipment of all kinds, and the “greening” of manufacturing including reducing pollution and waste by minimizing natural resource use, recycling and reusing what was considered waste, and reducing greenhouse gas emissions [3]. Growing numbers of manufacturers are finding that reducing resource use, waste, and pollution, along with recycling and reusing what was formerly looked at as waste, yields benefits not only in terms of an improved bottom line, but in terms of employee motivation, morale, and public relations [4].

The concept of cradle-to-cradle product design and production call for products to be designed and produced with an eye towards minimizing, or even eliminating, resource use, waste, and pollution [5, 6]. The drive to reduce fossil fuel use, carbon dioxide emissions, and other greenhouse gas emissions has been at the forefront of this movement. Moreover, people are encouraged to turn to consume products and services that have been produced from environmentally friendly manufacturing processes.

Thailand is also moving toward becoming a green manufacturing base in this region. It sees the need for going green in order for the people to live in a caring and sharing society, in a safe and sound environment. Also, in order to sustainably develop a competitive manufacturing industry, the focus on green manufacturing is now unavoidable.

2.2. Cutting-stock problem

The cutting-stock problem is the problem of filling an order at minimum cost or waste for specified numbers of lengths of material to be cut from given stock lengths of given cost [7]. It is one of the cutting and packing problems which are easy to state but difficult to solve (NP hard). The standard problem is defined as follows: given a set of small and large objects, how the small objects should be obtained from a large one in order to optimized a given criterion.

There are two main approaches to solve this problem: exact algorithm and heuristic methods. Exact algorithm is mainly based on linear programming, dynamic programming and branch-and-bound techniques [8]. Heuristic methods have greater flexibility in taking into account problem specific constraints and offer a trade-off between quality of a solution and its computational effort. Some of the heuristic methods used in solving cutting-stock problem are genetic algorithm [8-9], particle swarm optimization [10-11], simulated annealing [11-12], ant colony [13], etc.
For one dimensional cutting-stock problem, most of the approaches are based on linear programming models that can be divided into four categories 1) the assignment formulations 2) the pattern-oriented formulation 3) the one-cut formulation and 4) the flow models [8]. The implantations have proven that it can increase yield, decrease production cost, minimize usable waste and reduce carbon emission [1, 8, 13-14].

Various commercially available software was invented for specific applications such as sawmilling, metal and sheetmetal working, plywood cutting, etc. However, most SMEs cannot seek benefits from these available tools due to affordability and complexity of learning and integrating to the existing production planning system.

3. Methodology
In order to generate cutting plan for pine wood stock cutting based on production demand, two steps are required. First, all feasible one dimensional cutting pattern must be generated for all different length of raw pine wood. Second, solving the linear programming model to fine the optimal cutting plan based on the given demands. To facilitate these steps, Microsoft Excel spreadsheet is developed. The add-in OpenSolver, the open source linear, integer and non-linear optimizer for Microsoft Excel, is utilized to solve the linear programming model. The implementation of the optimized cutting plan will lead to reduction of production cost and carbon footprint which then be calculated and compared to the condition before implementation.

3.1. Pattern Generation Algorithm
A pattern is a plan of how to cut a given set of item from a stock material. In order to generate feasible cutting patterns for any length of raw pine wood, the algorithm was developed using logical operation sequence which satisfies the condition stated below:

\[ \sum_{i=1}^{n} a_{ijk} l_i \leq L_k \]  

where  
- \( L_k \) is the length of raw pine wood; \( k = 1, 2, \ldots, p \) 
- \( l_i \) is the length of item \( i \) in descending order; \( i = 1, 2, \ldots, n \) 
- \( a_{ijk} \) is the number of item \( i \) in the cutting pattern \( j \) cut from raw pine wood length \( k \) 
- \( P_{jk} \) is a cutting pattern \( j \) of the raw pine wood length \( k \); \( j = 1, 2, \ldots, m \)

For each \( L_k \) for all \( k = 1, 2, \ldots, p \)

Step 1: Set \( i = 1, j = 1 \)

Step 2: Cut the maximum number of \( l_i \) to generate the first pattern using; 
\[ a_{ijk} = \left\lfloor \frac{L_k}{l_i} \right\rfloor \]

Calculate the waste material (off-cuts) of pattern \( j \) using raw pine wood length \( k \); 
\[ W_{jk} = L_k - a_{ijk} l_i \]

Step 3: Compare \( W_{jk} \) with other \( l_i \)
If \( W_{jk} < l_i \)  
Then \( a_{ijk} = 0 \),  
Else  
\[ a_{ijk} = \left\lfloor \frac{W_{jk}}{l_i} \right\rfloor \]

\[ W_{jk} = L_k - \sum_{i=1}^{n} a_{ijk} l_i \]
Repeat Step 3 for all \( i = i+1, \ldots, n \)
Step 4: Generate next pattern \( j = j+1 \)

\( i_{last} \) = the last \( i \) where \( a_{i,j-1,k} \geq 1 \) and \( i \neq n \)

for all \( i = 1, 2, \ldots, i_{last}-1 \); \( a_{ijk} = a_{i,j-1,k} \)

for \( i = i_{last} \); \( a_{ijk} = a_{i,j-1,k} - 1 \)

for all \( i = i_{last}+1, \ldots, n \); \( W_{jk} = L_k - \sum_{l=1}^{n} a_{ijk}l_l \) then repeat Step 3

Repeat Step 4 until \( a_{ijk} = 0 \) for all \( i = 1, 2, \ldots, n-1 \)

The patterns generated are arrange such that;

\[
\begin{bmatrix}
    p_{11} & a_{111} & \cdots & a_{1n1} & W_{11} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    p_{m1} & a_{1mp} & \cdots & a_{nm1} & W_{m1}
\end{bmatrix}
\]

\[
\begin{bmatrix}
    p_{1p} & a_{11p} & \cdots & a_{1np} & W_{1p} \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    p_{mp} & a_{1mp} & \cdots & a_{nmp} & W_{mp}
\end{bmatrix}
\]

3.2. Linear Programming Model

The stock cutting process are subjected to two conditions; 1) the available stocks \((s_k)\) have different length and are limited in number 2) the number of item cut from available stocks must meet the production demand \((d_i)\). Since, the objective of the stock cutting is to minimize material waste (off-cuts), the cutting pattern that yield minimum material waste must be selected. Therefore, utilizing mixed-integer linear programing for minimizing waste (off-cuts) in the stock cutting process, the mathematical model can be stated as follow:

Minimize

\[
\sum_{k=1}^{p} \sum_{j=1}^{m} W_{jk} X_{jk}
\]  \hspace{1cm} (2)

Subject to:

\[
\sum_{j=1}^{m} \sum_{k=1}^{p} a_{ijk} X_{jk} = d_i \quad \forall \ i = 1, \ldots, n
\]  \hspace{1cm} (3)

\[
\sum_{j=1}^{m} X_{jk} \leq s_k \quad \forall \ k = 1, \ldots, p
\]  \hspace{1cm} (4)

\[
a_{ijk} \geq 0 \text{ and integer} \quad (5)
\]

\[
X_{jk} \geq 0 \text{ and integer} \quad (6)
\]

where \( X_{jk} \) is a number of times that pattern \( j \) is cut in the stock length \( k \)

The total waste generated can be defined as:

\[
\text{Total waste} = \sum_{k=1}^{p} \sum_{j=1}^{m} W_{jk} X_{jk}
\]  \hspace{1cm} (7)

The total number of raw pine wood length \( k \) used as stocks can be defined as:
Total number of raw pine wood length \( k = \sum_{j=1}^{m} X_{jk} \)  

(8)

The total number of item \( i \) after complete the cutting can be defined as;

\[
\text{Total number of item } i = \sum_{j=1}^{m} \sum_{k=1}^{p} a_{ijk}X_{jk}
\]

(9)

3.3. Spreadsheet Development

The aim of this development is to be used in the small and medium sizes enterprises (SMEs) and also to be easily integrated into the existing production planning and control sequence. Thus, the most commonly used software in production planning of SMEs, Microsoft Excel is selected as a platform for implementation. Due to the limitation of Solver add-in in Microsoft Excel in terms of number of variables, the open-source add-in, OpenSolver is utilized to solve the developed mixed-integer linear programing problem. The following steps are used in order to develop the spreadsheet and solve for the optimal cutting plan;

1) Define the multiple lengths of raw pine wood and item to be cut.
2) Generate all the cutting pattern as a database.
3) Implement the developed linear programming model in one sheet. Calculate the value of objective function and all constraint values.
4) Install the add-in, OpenSolver, into Microsoft Excel and define the model (objective cell, variable cells and constraints).
5) Input the production demands of each item and the number of available stocks, then allow the OpenSolver to solve for the optimal solution.
6) The cutting plan is automatically generated based on the calculated solution from previous step using Microsoft Excel function.

4. Results and Discussions

To demonstrate the applicability of the developed model, the case study related to the cutting problem encountered at an SME wooden pallet production firm in Thailand is presented and discussed.

4.1. The Case Study

Pine wood are imported from New Zealand, shipping as a container. The imported pine wood is cut to the standard rectangular profile of 150 × 100 mm with the length \( (L_k) \) of 4.2, 4.8, 5.4 and 6.0 m randomly. The average cost of imported pine wood (include shipping cost) is 265 Baht/foot\(^3\). The pine wood has to be cut down to the item of required sizes depending on the model of pallets to be made. The length of each item \( (l_i) \) are shown in Table 1. The numbers of pine wood to be cut to each length are calculated based on the production schedule. The current cutting plan utilizes the simplicity of cutting process by having only single length of cut for each pre-defined stock. This method is good in terms of production rate but generate lots of waste as shown in Figure 1. The analysis of cost and waste generated using current cutting plan for one month is shown in Table 1.
Figure 1. The raw pine wood (stock) and its waste (off-cuts)

Table 1. The analysis of current cutting plan

| No. | Length (mm) | Demand (piece) | Stock length (mm) | Required stock (piece) | Stock volume (foot³) | Waste volume (foot³) |
|-----|-------------|----------------|-------------------|------------------------|----------------------|----------------------|
| 1   | 2316        | 789            | 4800              | 395                    | 1004.36              | 35.15                |
| 2   | 2200        | 254            | 4800              | 127                    | 322.92               | 26.91                |
| 3   | 1650        | 468            | 5400              | 156                    | 446.24               | 37.19                |
| 4   | 1460        | 554            | 6000              | 139                    | 441.79               | 11.78                |
| 5   | 1140        | 4686           | 6000              | 938                    | 2981.29              | 149.06               |
| 6   | 1120        | 1179           | 4800              | 295                    | 750.09               | 50.01                |
| 7   | 980         | 969            | 4800              | 243                    | 617.87               | 113.28               |
|     |             |                |                   |                        |                      |                      |
|     | Total       |                |                   |                        | 6564.56              | 423.38               |
|     | Cost/month  | 1,739,609      | 112,195           |                        |                      |                      |

4.2. Implementing Optimal Cutting Plan
After develop the spreadsheet, using the same production demand and solve for the optimal cutting plan (assuming unlimited number of stocks). The result of the developed model suggests the optimal cutting plan as shown in Table 2.

Table 2. Optimal cutting plan generated by the developed model

| Stock length (mm) | Required stock (piece) | No. of item to be cut with the length of (mm) |
|-------------------|------------------------|-----------------------------------------------|
| 4800              | 394                    | 2316 2200 1650 1460 1140 1120 980              |
|                   | 1                      | 1 1                                          |
| 5400              | 107                    | 1 2                                          |
|                   | 304                    | 3 1                                          |
| 6000              | 254                    | 1 1                                          |
|                   | 554                    | 1 3 1                                        |
|                   | 371                    | 5                                             |
|                   | 103                    | 5                                             |
| Number of each item | 789 254 468 554 4686 1179 969 |
Based on the optimal cutting plan, the required stock volume, cost and waste are calculated and compared as shown in Table 3. It can be seen that, using the new approach can reduce waste up to 70.86% and reduce production cost up to 4.68% or 977,352 Baht/year.

**Table 3. The comparison of current cutting plan and optimal cutting plan.**

| List                          | Current cutting plan | Optimal cutting plan | Change     |
|-------------------------------|----------------------|----------------------|------------|
| Volume of stock required (foot³) | 6564.56              | 6257.22              | -307.34    |
| Cost of stock (Baht/month)     | 1,739,609            | 1,658,163            | -81,446 (4.68%) |
| Volume of waste (foot³)        | 423.38               | 123.37               | -300.01    |
| Cost of waste (Baht/month)     | 112,195              | 32,693               | -79,502 (70.86%) |

4.3. **Comparison of Carbon Emission**

The process-based analysis is used to estimate the carbon emission starting from harvesting of pine wood till finishing the stock cutting process. Based on, the results shown in Table 4, the amount of carbon emission from the pine wood cutting process can be reduced by 22,713 kg CO₂-e/year or approximately 5.32% reduction. The impact of reducing the waste generated during the pine wood cutting process go beyond the pallet manufacturer. The carbon emission from harvesting, sawmilling and transportation are also reduced.

**Table 4. The comparison of carbon emission.**

| Process/Activity          | Emission factor (kg CO₂-e/unit) | Input | Carbon Emission (kg CO₂-e/year) |
|---------------------------|----------------------------------|-------|-------------------------------|
|                           |                                  | Current cutting plan | Optimal cutting plan | Current cutting plan | Optimal cutting plan |
| Forest harvest            |                                  |                   |                   |                   |                   |
| Gasoil (l)                | 2.84                             | 41639             | 39691             | 118256            | 112722            |
| Transport to sawmill      |                                  |                   |                   |                   |                   |
| Gasoil (l)                | 2.84                             | 11462             | 10926             | 32552             | 31029             |
| Sawmill                   |                                  |                   |                   |                   |                   |
| Gasoil (l)                | 2.84                             | 9135              | 8708              | 25944             | 24730             |
| Electricity (kWh)         | 0.39                             | 190391            | 181481            | 74252             | 70777             |
| Transport to manufacturer |                                  |                   |                   |                   |                   |
| Sea freight (Tonne-km)    | 0.008                            | 13751553          | 13008226          | 110012            | 104066            |
| Truck (Tonne-km)          | 0.62                             | 100285            | 94864             | 62177             | 58816             |
| Stock cutting             |                                  |                   |                   |                   |                   |
| Electricity (kWh)         | 0.39                             | 4188              | 4188              | 1633              | 1633              |
| Waste handling            |                                  |                   |                   |                   |                   |
| LPG (l)                   | 1.5                              | 1560              | 455               | 2341              | 682               |
| **Total Carbon Dioxide Equivalent Emission** |                           | 427168            | 404455            |

Note: Emission factors obtained from [15-17]
5. Conclusions
Applying one dimensional cutting-stock problem to the wooden pallet industry can yield benefits in terms of both cost and carbon emission reduction. This is in fact a good practice toward green manufacturing. The developed linear programing model implemented on basic software such as Microsoft Excel and open source add-in OpenSolver has proven to be able to quickly and correctly offer the optimal cutting plan. Raw material waste decrease up to 70.86% resulting in a cost reduction of 977,352 Baht/year. Furthermore, it leads to a reduction of carbon emission in the life cycle of imported pine wood. The amount of carbon dioxide equivalent is reduced by 22,713 kg CO₂-e/year or approximately 5.32% reduction. The method developed in this research is very affordable and can easily be integrated to the existing production planning system.

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