แบบจำลองโลจิสติกส์ย้อนกลับสำหรับการรีไซเคิลพลาสติกในประเทศไทย

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บทคัดย่อ

เนื่องจากปัจจุบันปัญหาขยะที่มาจากพลาสติกเป็นประเด็นที่สำคัญและหลีกเลี่ยงไม่ได้ แต่ว่าเปอเซนต์การรีไซเคิลของขยะพลาสติกในประเทศไทยยังมีค่าต่ำอยู่ เพราะในการที่จะสร้างโรงงานรีไซเคิลพลาสติกนั้นต้องใช้เงินลงทุนเป็นจำนวนมาก ดังนั้นพลาสติกที่ใช้แล้วจำนวนมากไม่ได้ถูกนำมารีไซเคิลเพื่อก่อให้เกิดประโยชน์ ส่วนใหญ่จะถูกเผาเพื่อทำลายและปล่อยก๊าซพิษเข้าสู่บรรยากาศโลก หรือถูกส่งไปฝังดินตามแหล่งจัดเก็บขยะต่างๆ เพื่อที่จะการวางแผนโครงสร้างพื้นฐานของระบบโลจิสติกส์แบบย้อนกลับที่มีประสิทธิภาพเป็นสิ่งที่สำคัญยิ่งเพื่อจะนำมาส่งเสริมกิจกรรมการรีไซเคิลนี้ให้ประสบความสำเร็จ ในบทความวิจัยนี้ ได้นำเสนอวิธีการที่จะออกแบบระบบย้อนกลับในรูปแบบของตัวเลขเต็มแบบผสมแบบเป็นเชิงเส้น หรือ Mixed-integer Linear Programming ที่คลอบคลุมการเพิ่มเปอเซนต์การรีไซเคิล และ แนวทางการจัดการกับที่ฝังขยะในอนาคต จากผลกรณีศึกษาเบื้องต้นพบว่า นโยบายของภาครัฐในการจัดการกับขยะพลาสติก จะส่งผลต่อการวางแผนสร้างโครงสร้างในระยะยาวเป็นอย่างมาก นอกไปจากนี้บทความนี้ยังมีการนำเสนอการใช้ในทางปฏิบัติของแบบจำลองขนาดจริงสำหรับการรีไซเคิลพลาสติกในประเทศไทย

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Abstract

Plastic waste has become an unavoidable problem in Thailand. However, the recovery percentage of plastic in Thailand is still low due to the high cost in constructing and operating the plastic recycle plants. Therefore, most of the plastic wastes are either burnt to destroy or sent to the landfills. In order to be financial viable, an effective reverse logistics infrastructure is required to support the product recovery activities. In this research, an approach for designing reverse logistics infrastructure is presented in the form of mixed-integer linear programming. This formulation includes the feature to raise the recovery percentage and manage the landfill economically in the long run. The preliminary result from the small case study shows that government policy on recovery percentage is vital to the long term infrastructure design. In addition, a practical application of the model for Thailand's plastic recycling is discussed.

Keywords: reverse logistics, Modeling, Plastic Recycling

1. INTRODUCTION

According to the report of Pollution Control Department [5], the amount of solid waste in Thailand accounts for almost 40,000 ton a day in year 2005. That equals to 14.5 million tons a year. Furthermore, this number has an upward trend since year 1993 as shown in Figure 1. According to the study by [6], it is reported that plastic waste accounts for about 14 percents of all generated solid waste amounts in year 2000. However, the percentage of plastic recovery is low. The recovery rate of plastic waste is only 23 percents in year 2000 [6]. In this research, we focus our attention on plastic waste in Thailand. Moreover, the usage of plastic has a tendency to increase at 4.69 percents a year. Hence, the amounts of plastics that end up in the landfill are enormous. As a result, Thai governments have attempted to reduce the amount of plastic in the waste stream. For example, the energy department [4] plans to set up a facility in Samutprakarn to recycle plastic waste and convert them into oil using polymer energy technology. This facility could reduce plastic waste for the amount of 6 millions ton a day. However, the current situation of handling solid waste in Thailand still faces an uphill challenge. According to [1,2,3], only about 35% of the solid wastes collected from other parts of Thailand except Bangkok are properly managed. The remaining amount is piled up in open dumping so that it could dissolve by itself. This method is environmentally prohibited. Therefore, Thailand is in need of more properly managed landfills and plastic recycling facilities.

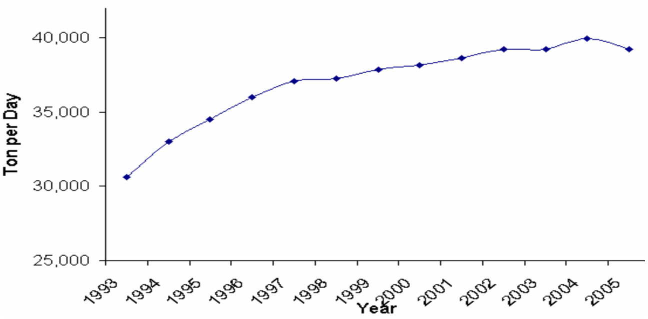

Figure 1: Average Amounts of Solid Waste Per Day in Thailand from year 1993-2005

As the technology in plastic recycle is till being developed, the product recycling process as a whole cannot be economically achieved without an effective design of the reverse logistics system. In this research, we present a mathematical model for strategic planning of the plastic recycling system as a mixed integer linear programming (MILP). This model captures an attempt to raise the recovery percentage of plastic waste by opening new recycle facility and properly manage the landfills to satisfy the needs in the long run. A preliminary result of the small case study example is shown and the guidelines to study a practical application of Thailand are also presented.

2. LITERATURE REVIEW

2.1. Philosophy of Plastic Recycle in General

In recent years, there have been a lot of publications concerning the plastic recycling [7, 12, 19]. Most of the researches focus on developing plastic recycling technology. The recent technology discovery, called polymer energy technology [19], has brought a new venue to transform post-consumer plastics into oil. However, the investment cost is still high and the technology development is still on-going. China is one of the nations that launched some pilot plants. However, according to Zhang [24] who present the current situation of recycling waste plastics into oil from both technology and economics standpoints in China, she learned that there are more tasks to be done to constitute the standards for process and to manage the way the recycling plant should run.

2.2. Facility Location Allocations and Distribution Model

The design of reverse productions systems have emerged as topics of recent interests. Fleischmann *et al.* [13] present a characterization of logistic networks for product recovery. Carter and Ellram [10] also give a review of the literature on reverse logistics. Ammons *et al.* (1999) [8] propose a generic mixed integer programming model to determine the infrastructure of the recovery system and present common features of the reverse production system. For researches that study how to allocate recycle facilities in reverse logistics systems, there have been many studies in different types of discarded products such as non-electronic products and electronic products.

For non-electronic products, Caruso et al. [11] develop a multi-objective mathematical model of location allocation for planning the urban solid waste management system. Kroon and Vrijens [17] study a case in Netherlands, a large reverse logistics organization service for returnable containers. Realff *et al.* [20] develop a mixed integer programming model to provide a decision-making tool for carpet recycling infrastructure design. Louwers *et al.* [18] also propose a facility location allocation model for reusing carpet materials. The model has been used to study the applications in Europe and U.S.A. Schultmann *et al.* [21] develop a mixed integer programming model to solve a facility location problem. The authors apply the model to a case study of recycling networks for spent batteries in Germany.

For electronic products, Shih [22] develops a mixed integer programming model to study a reverse logistics system planning for electrical appliances and computers in northern Taiwan. Ammons *et al.* [9] look at electronic recovery problem under uncertainty in terms of costs, prices, and volumes. They present mathematical programming tools to support robust strategic decision making. Other researches focusing on electronic products include Krikke *et al.* [16], and Jayaraman *et al.* [14, 15].

2. REVERSE LOGISTCS MODEL FOR PLASTIC RECYCLE

In order to understand the material flows of solid waste management in Thailand, we formulate the plastic reverse logistics network design as a mixed integer programming (MILP model). This formulation is able to capture the network design problem at the strategic level. The goal of the model is to identify the infrastructure setting that minimizes the total cost of the overall setting over multiple time periods, subject to a set of constraints and assumptions. An important goal that we want to accomplish is to study how we should design the infrastructure with the least cost. In this model, we make the following assumptions: (1) all parameters are deterministic, (2) costs functions are linear functions, and (3) the location of all possible sites are predetermined. The continuous variables in the model represent the flows of materials and the integer variables in the model represent the existences of the potential infrastructures (Ammons *et al.* [9]). The customer in the model can present the factories that purchase the recycled factories. In words, we can describe the objective function and the constraints of the MILP model as follows:

Minimize: Total Cost = Total investment and operating costs
Subject to: (a) Minimum recovery percentage constraints
(b) Flow balance between sites and between time periods for each material constraints
(c) Transportation and processing capacity constraints
(d) Upper bound for each site constraints
(e) Demand and supply constraints
(f) Closing of Full-capacity Landfill constraints
(g) Site opening and closing constraints
(h) Logical, non-negativity, and binary constraints

Constrain (a) ensures that the opened processing sites will process the total amount of plastics not less than the predetermined percentage. Constrain (b) enforces the balance of the flow-in and flow-out of materials at each site. Constrain (c) make sure that the capacity of machines and transportation vehicles at each location site do not exceed their capacity. Constrain (d) enforces the operating capacity of each site. Constrain (e) ensures that the amount of materials generated from the source must be all processed. Constrain (f) enforces the landfill site with full capacity to close itself down and will no longer be available for use at later time periods. Constrain (g) controls the logical relationship of binary variables representing site opening and closing actions. Constrain (h) enforces logical relationships between variables and non-negativity of variables. Next, we introduce the indices, parameters and decisions variables in the MILP in tables 1, 2, and 3 respectively.

Table 1 Indices in MILP model

Indices	Description	indices	Description
s	Provinces	i, j	Nodes of sites
i_p^l	Processing sites (landfill)	i_p	Processing sites
c	Customer sites	m	Transportation mode
k, *q*	Material types	*P*/*p*	Main/sub-process types

Table 2 Parameters in MILP model

Parameters	Definition and description
$F_{it}^{(oper)}$	Fixed operating costs at site i at time period t
$F_{it}^{(open)}$, $F_{it}^{(close)}$	Fixed opening and closing cost at site i at time period t
$F_{ijmt}^{(tr)}$, $F_{icmt}^{(tr)}$	Fixed cost per vehicle to transport materials from site i to j/customer c by transportation mode m at time period t.
$F_{iPt}^{(pr)}$	Fixed cost for one unit of the main-process P at site i at time period t
$V_{ipt}^{(pr)}$	Processing cost per standard unit for sub-process p at site i at time period t
$V_{ijmt}^{(tr)}$,$V_{icmt}^{(tr)}$	Transportation cost per standard unit of material, to transfer material from site i to j/customer c at time period t
ρ_{kp} , ρ'_{kp}	The proportion of material type k consumed by process p The proportion of material type k produced by process p
$C_{ikj}^{(tr)}$,	The maximum amount of material k that a vehicle can transfer per time period from site i to j at time period t
$C_{pP}^{(pr)}$	The maximum amount of material that a machine of main process P, sub-process p can operate per time period
$H_{ijmt}^{(tr)}$	the maximum number of vehicles in transportation mode m to transfer material from site i to j at time period t
$H_{iPt}^{(pr)}$	The maximum number of machines of main-process P at site at time period t at time period t
$G_{ijmt}^{(tr)}$	=1 if vehicles in transportation mode m to transfer material from site i to j must be utilized at time t; 0 otherwise
$G_{iPt}^{(pr)}$	=1 if machines of main process P at site i must be utilized at time t; 0 otherwise
$A_{ijmt}^{(tr)}$	=1 if vehicles in transportation mode m to ship material from site i to j is allowed to be utilized; 0 otherwise
$A_{iP}^{(pr)}$	=1 if machines of main process P at site i is allowed to be utilized; 0 otherwise
S_{skt} , D_{kct}	= the amount of supply of material k at province s at time period t = the amount of demand of material k from customer c at time period t
CAP_i	= the maximum amount of all materials that processing site i can operate at the beginning
$LCAP_i$	= the minimum capacity amount of all materials that landfill i can hold before closing down
M	= positive large number
b_t	= the minimum percentage of recovery rate of plastic at time period t

Table 3 Decision variables in MILP model

Decision Variables	Definition and description
$y_{it}^{(oper)}$	=1 if site i is opened and operating 0 otherwise
$y_{it}^{(open)}$, $y_{it}^{(close)}, \overline{y}_{it}^{(close)}$	=1 if site i is just opened at the beginning of time period t 0 otherwise =1 if site i is just closed at the end of time period t-1, dummy variable
$y_{ijmt}^{(tr)}$	the number of vehicles needed to transfer materials from site i to j by transportation mode m at time period t
$y_{iPt}^{(pr)}$	the number of machines of main process P needed at site i at time period t
$x_{ikj}^{(tr)}$	the amount of material k transferred from site i to site j at time period t
$x_{ipt}^{(pr)}$, $x_{ipPt}^{(pr)}$	the amount of material processed by sub-process p at site I at time period t, the amount of material processed by main-process P, sub-process p at site i at time period t
$ICAP_{it}$	= the amount of all materials that processing site i can operate at time period t

According to the notation above, the MILP model which aims to incorporate a multi-product, multi-process, multi-time period network design problem can be stated as:

Minimizing $$\sum_{i,t} F_{it}^{(oper)} y_{it}^{(oper)} + \sum_{i,t} F_{it}^{(open)} y_{it}^{(open)} + \sum_{i,t} F_{it}^{(close)} y_{it}^{(close)} + \sum_{i,j\neq i,m,t} F_{ijmt}^{(tr)} y_{ijmt}^{(tr)} + \sum_{i,j\neq i,k,m,t} V_{ijmt}^{(tr)} x_{ikjmt}^{(tr)} + \sum_{i,P,t} F_{iPt}^{(pr)} y_{iPt}^{(pr)} + \sum_{i,p,t} V_{ipt}^{(pr)} x_{ipt}^{(pr)}$$

Constraints **Subject to:**

(a) $\sum_{i,j\neq i,k\in Plastics,m} x_{jkimt}^{(tr)} \geq b_t \sum_{i,k\in Plastics} S_{ikt} \qquad \forall i \in i_p, t$ (1)

(b) $\sum_{j\neq i,m} x_{jkimt}^{(tr)} - \sum_{j\neq i,m} x_{ikjmt}^{(tr)} - \sum_{c,m} x_{ikcmt}^{(tr)}$ (2)

$+\sum_{p,P} \rho'_{kp} x_{ipP}^{(pr)} - \sum_{p,P} \rho_{kp} x_{ipPt}^{(pr)} = 0 \qquad \forall i \in i_p, k, t$

(b) $x_{ipt}^{(pr)} = \sum_{P:p\in P} x_{ipPt}^{(pr)} \qquad \forall i, p, t$ (3)

(c) $\sum_{k} \frac{x_{ikjmt}^{(tr)}}{C_{ikjm}^{(tr)}} \leq y_{ijmt}^{(tr)} \qquad \forall i, j \neq i, m, t$ (4)

(c) $\sum_{p\in P} \frac{x_{ipPt}^{(pr)}}{C_{pP}^{(pr)}} \leq y_{iPt}^{(pr)} \qquad \forall i, P, t$ (5)

(d) $\sum_{jkmt} x_{jkimt}^{(tr)} \leq CAP_{it} \qquad \forall i, t$ (6)

(e) $\sum_{ikjm} x_{ikjmt}^{(tr)} = S_{ikt} \qquad \forall i \in i_s, k, t$ (7)

(e) $\sum_{i,m} x_{ijcmt}^{(Tr)} \leq D_{ckt} \qquad \forall k, c, t$ (8)

(f) $ICAP_{i0} = CAP_i \qquad \forall i \in i_p^l$ (9)

(f) $$ICAP_{it} = ICAP_{t-1} - \sum_{jkm} x^{(tr)}_{jkim,t-1} \qquad \forall i \in i^l_p, t : t > 1 \qquad (10)$$

(f) $$y^{(close)}_{i,t+1} - 1 \leq M\overline{y}^{(close)}_{i,t+1} \qquad \forall i \in i^l_p, t \qquad (11)$$

(f) $$LCAP_i - ICAP_{it} < M(1 - \overline{y}^{(close)}_{i,t+1}) \qquad \forall i \in i^l_p, t \qquad (12)$$

(g) $$y^{(close)}_{i,t-1} \leq y^{(close)}_{it} \qquad \forall i, t : t > 1 \qquad (13)$$

(g) $$y^{(oper)}_{it} - y^{(oper)}_{i,t-1} \leq y^{(open)}_{it} \qquad \forall i, t : t > 1 \qquad (14)$$

(g) $$y^{(oper)}_{i,t-1} - y^{(oper)}_{it} \leq y^{(close)}_{it} \qquad \forall i, t : t > 1 \qquad (15)$$

(g) $$y^{(oper)}_{it} \leq y^{(open)}_{it} \qquad \forall i, t = 1 \qquad (16)$$

(h) $$G^{(tr)}_{ijmt} \leq y^{(tr)}_{ijmt} \leq H^{(tr)}_{ijmt} A^{(tr)}_{ijmt} y^{(oper)}_{it} \qquad \forall i, j \neq i, m, t \qquad (17)$$

(h) $$G^{(tr)}_{ijmt} \leq H^{(tr)}_{ijmt} A^{(tr)}_{ijmt} y^{(oper)}_{jt} \qquad \forall i, j \neq i, m, t \qquad (18)$$

(h) $$G^{(pr)}_{iPt} \leq y^{(pr)}_{ipt} \leq H^{(pr)}_{iPt} A^{(pr)}_{iPt} y^{(oper)}_{it} \qquad \forall i, P, t \qquad (19)$$

(h) $$x^{(tr)}_{ikjmt}, x^{(pr)}_{ipt}, x^{(pr)}_{ipPt} \geq 0 \qquad \forall i, k, j \neq i, t, p, P, m \qquad (20)$$

(h) $$y^{(oper)}_{it}, y^{(open)}_{it}, y^{(close)}_{it} \in \{0,1\} \qquad \forall i, t \qquad (21)$$

(h) $$y^{(tr)}_{ijmt} \in \{0,1,2,\ldots,H^{(tr)}_{ijmt}\} \qquad \forall i, j \neq i, m, t \qquad (22)$$

(h) $$y^{(pr)}_{iPt} \in \{0,1,2,\ldots,H^{(pr)}_{iPt}\} \qquad \forall i, P, t \qquad (23)$$

The objective function of the model is to minimize the total cost which includes all fixed costs and operating costs incurred while operating the reverse logistics network. The model also includes all constraints previously described. Next, we point out two new features of this model that represent recovery percentage requirement and landfill closing characteristic in problem. First, we want to raise the recovery percentage of plastics to a certain number in each time period. This can be done by enforcing the constraint (1). Second, we also carefully look at the capacity of the landfill which we define as processing site. Since the landfill capacity is limited and it has to close down when it reaches its capacity, we modify the model to incorporate this feature. We assume that this landfill can process all material types. This feature is done by constraints (9) – (12).

The objective function includes two important costs which are the recycling processing cost at the processing sites if they are open and operating and landfill cost at the landfill site. By nature of operation, the cost to open and operating landfill is lower than the cost to open and operating the recycling plant. Therefore, by enforcing the minimum recovery percentage, this mathematical formulation can help the decision maker plan ahead how to reduce the materials shipped to the landfill and increase the recycled materials processed at the processing sites. The recycling materials in this model are the used plastic products such as broken plastic chairs, plastic water bottles, etc.

3. SMALL CASE STUDY EXMPLE

In order to validate the model, we have performed the numerical study to imitate the real-sized case study. There are total of 76 sources which are located at all provinces in Thailand. We assume 15 potential collection sites or 3 collection sites in Northern, Southern, Eastern, Northeastern, and Central regions. Also, we assume that there are five potential landfill sites and each one is located in each region with one site already operating in central region. We also assume five potential processing sites and each one is located in each region with one site already operating in central region. Each processing site has the same capacity. Each processing time can perform 2 processing tasks; sorting and grinding. We only consider plastic materials here and there is only one mode of transportation which is by truck. The problem is solved for 3-year period.

We use the population in each province to estimate the plastic waste. According to [6], we assume that the total supply for the first year is 1,094,637 ton and it's increased by 5% for the next two years. With this information, the supply of plastic waste in each province can be obtained. The transportation cost is estimated from the truck transportation mode and the distance between two sites. The model is developed in GAMS using CPLEX solver and performed on a Pentium (R) 4 CPU, 2.40 GHz computer with 1 GB of RAM. Note that to make this paper concise, we have omitted some details required for this case study.

We consider two cases – 5% and 30% recover percentage. The summary of associated costs from case 1 and case 2 is shown in Table 1 and Table 2 respectively.

Table 1: Summary of Associated Costs for 5% Recovery Percentage in Each year

Type	**Costs ($B)**	**Percent of Total Costs**
Collection Cost	5,054,789	31%
Processing Cost (Fixed + Variable)	1,024,879	6%
Landfill Cost	1,532,486	9%
Transportation Cost	8,687,450	53%
Total	*16,299,604*	*100%*

Table 2: Summary of Associated Costs for 30% Recovery Percentage in Each year

Type	**Costs ($B)**	**Percent of Total Costs**
Collection Cost	5,248,470	16%
Processing Cost (Fixed + Variable)	10,489,657	33%
Landfill Cost	7,054,896	22%
Transportation Cost	9,123,654	29%
Total	*31,916,677*	*100%*

The results from Table 1 and Table 2 show that in order to achieve 30% recovery percentage it requires much more cost to construct and operate the processing sites. This recovery percentage is usually impacted by the government policy. In the case 1, the small recovery percentage allows most of the plastic waste to be shipped to the landfill because it is cheaper to open new landfills and operate them. Nevertheless, the result is different in case 2 which requires a higher recovery percentage. In this case, the processing sites are forced to open and operate the higher amount of plastic waste to meet the recovery percentage. Since the overall cost of recycling plant is much higher than the cost of operating landfills, the overall cost in this case becomes higher. It is important to address that the transportation costs account for a higher percentage of total costs. This suggests that the location of the infrastructure has a significant impact on the total cost. In any rate, this model suggests that it can be used to compare many recycling alternatives such as choosing between dumping plastic waste into the landfill and recycling plastic waste as much as possible. This can be done by solving the problem with different recycling percentage.

4. LARGE SCALED CASE STUDY GUIDLINES

Hereafter the guidelines for practical case study for Thailand are discussed. In order to generate case study for Plastic situation in Thailand by employing the proposed MILP, careful data collection is needed.

For example, according to the Pollution Control Department report (2005), there are 96 municipal landfills in Thailand. However, these landfills will eventually be filled one day. By using the model, we can plan ahead where and when we should plan to build new landfills to properly manage the solid waste which does not only include plastics. We can look at the decision on yearly basis. Even though this is not an ideal situation, it is better than leaving the solid waste on the opened ground. That will create more problems for the environment of Thailand.

All the steps needed to generate the case study are as proposed as follows:

1. Determine all material types
2. Determine the source sites, processing sites (landfill, recycling facility, and sorting facility)
3. Determine the potential and currently available processes in each processing sites
4. Retrieve data for the supply of solid waste for each province
5. Estimate the cost of the processing infrastructure and its associated operating costs
    - 5.1 Fixed Cost
    - 5.2 Variable Cost
6. Estimate the transportation cost for transferring the materials between sites
    - 6.1 Fixed Cost
    - 6.2 Variable Cost
7. Obtain the operating capacity of all sites per year
8. Obtain the distance matrix for all considered sites and sources
9. Obtain the maximum capacity of the landfill site and its current capacity
10. Input the data into the MILP model. This research uses a commercial solver GAMS as a front-end interface to CPLEX to determine the optimal solution of the model.
11. Analyze the results and rerun more models with different parameters

5. CONCLUSION

In this research, we propose a mathematical model for the design of reverse logistic system and offer a guideline to the large-scale problem for the planning of countrywide plastic recycling program for Thailand. The key decisions in the model are resource allocations, facility locations, and material flows in the system. Several realistic characteristics of the reverse supply chains system are included into the presented mathematical model. These characteristics include (1) the possibility of raising recycling percentage and (2) the possibility of managing the landfills in the long run. In addition, based on the small case study, it is shown that the recovery percentage which depends on government policy can have a critical impact on the design of the long term infrastructure of the reverse logistics.

The future work includes employing the proposed model into a case study of Plastics Recycle in Thailand. The model would be a large scale with millions of variables and constraints. Gathering the necessary data and making proper assumptions on the parameters are vital to the results of the case study. The results may be helpful to the designers of solid waste collection and processing systems in Thailand aiming to raise the percentage of plastic recycle economically. Thus, Thailand will see less plastic wastes in the environment and raise the quality of life for Thai people.

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