International Journal of Technology 12(2) 390-400 (2021)
Received August 2019 / Revised September 2019 / Accepted March 2021

International Journal of Technology

http://ijtech.eng.ui.ac.id

A Construction Heuristic for the Bin-Packing Problem with Time Windows: A Case Study in Thailand

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Abstract. This study aims to improve the efficiency of distribution for food manufacturers, extending previous research that solved the bin-packing problem with time windows (BPPTW) using integer programming (IP) and Microsoft Excel Solver. The drawback of this approach is that it has difficulty solving large problems. In the future, the number of customers is expected to increase, and therefore, we propose a construction heuristic that can solve the BPPTW within a shorter time. The algorithm was designed to allocate customers who had time window constraints first to ensure that only feasible solutions were generated. The program was written in Visual Basic for Applications (VBA) in Excel because it is convenient to use for decision makers. The data were then solved using a heuristic. The results showed that the heuristic can solve real problems with the optimal solution. We showed that, by using these two methods, the annual transportation cost is reduced by 23.23%, or 489,450 baht per year, and the computational time is drastically reduced. Next, we generated larger problems and compared the computational times for the two methods. We showed that the Solver cannot handle a problem involving more than 32 customers, and that it takes more time as the problem size increases. In contrast, the construction heuristic can solve the problem within 1 minute. Hence, it is more attractive to use our heuristic than IP as a decision support tool for a case company's transportation department.

Keywords: Bin-packing problem with time windows; Construction heuristic; Integer programming; Visual Basic for Applications

1. Introduction

In Thailand, transportation is one of the major activities contributing to the gross domestic product (GDP). The proportion of the GDP represented by logistics in Thailand in 2018 was 13.4%. Transportation made up the largest proportion, at 54.4%, and inventory and administration costs accounted for 36.6% and 9.0% of the GDP, respectively (NESDB, 2018). There is also an increasing trend toward transportation as a proportion of the GDP as the manufacturing industry grows. Transportation causes CO_2 gas emissions to the world. Mubarak and Zainal (2018) studied the framework for a company to calculate CO_2 emissions in Indonesia. The framework helped companies to assess CO_2 emissions to the environment. Transportation costs increase as fuel costs increase; however, without control

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doi: 10.14716/ijtech.v12i2.3366

over the fuel price, manufacturers can only focus on the reduction of transportation costs based on the planning and routing of transportation management. The precision of the routes and schedules of vehicles are logistics challenges, and transportation modeling is highly significant research (Pamitran et al., 2015). Transportation management is related to many activities, such as demand forecasting (Pradita et al., 2020), procurement planning (Deepradit et al., 2020), and transport between locations (Doungpattra et al., 2012).

This research focuses on a case study in the food industry, which outsources transportation to a third-party logistics (3PL) provider, although the transportation department of the manufacturer determines how many trucks are needed every week. In addition, there are limitations on the delivery time window and truck bans at certain times because of the Department of Transport regulations, which aim to reduce traffic jams in Bangkok and the metropolitan region. This makes the problem more difficult. Currently, the company's transportation department is inefficient and has high turnover. The staff spend about 3 hours managing the allocation of customers to the outsourcing trucks and deliveries are often late. Our research aims to solve the truck assignment problem in this case study with time window constraints. This research compares the proposed method with that of Ongarj and Ongkunaruk (2013) and addresses the limitations that arise when problem sizes become larger. These researchers formulated integer programming (IP) and solved the problem using a Solver in Microsoft Excel. However, this method exhibits a drawback when the number of customers increases. Hence, this research proposes a heuristic to solve the same problem and compares the quality of the solutions and computational times.

The case study problem is called the bin-packing problem with time windows (BPPTW), as defined by Ongarj and Ongkunaruk (2013). The problem involves determining which customer orders will be allocated to trucks to minimize the number of trucks used while satisfying demand and truck capacity. In addition, there are delivery time window constraints. The bin-packing problem (BPP) is an NP-complete and NP-hard problem, and it takes a long time to solve in the case of large problems (Garey and Johnson, 1979; Ongkunaruk, 2005; Delorme et al., 2016). Some research on the heuristics that have been proposed to solve the BPP (Martello and Toth, 1990; Coffman and Lueker, 1991; Fleszar and Hindi, 2002; Loh et al., 2008; Hemmelmayr et al., 2012; Ayob et al., 2013). Later, Ongkunaruk (2008) proved that the asymptotic worst case ratio of first fit decreasing is 11/9 by the maximum occupied technique. There is also a variant of the BPP known as the BPP with conflicts, in which there are conflicts determining components that cannot be packed in the same bin (Gendreau et al., 2004; Fernandes-Muritiba et al., 2010).

In 2013, the number of customers in Bangkok and the surrounding metropolitan area was 690, and this number has continued to rise since then, resulting in more challenges in solving the BPP. Staff determine how many trucks will be used to deliver the products based on their experience. Customers do not know when their products will be delivered because the drivers often fail to deliver according to the company schedule. Hence, the staff must reschedule and redo invoices, causing additional costs. In addition, the staff turnover rate in the transportation department is high, and new staff take more time to solve this problem. Since the transportation cost per shipment is fixed, the number of trucks used should be minimized. The level of customer service required is 100%. The transportation cost is the same for customers located in the same zone. Six four-wheeled trucks are used, with a capacity of 220 boxes per truck. Although the delivery time is scheduled from 5 a.m. to 3 p.m., some customer orders must be delivered between 5 a.m. and 8 a.m. because of traffic regulations. The problem has been simplified to give at most two customer groups that can be delivered to using the same truck, as defined by the time window constraint. In addition, the company has established a rule that at least one truck must be dedicated to each zone.

2. Methods

This section is divided into four parts. First, the zoning of customers location was performed to reduce the problem size. Second, the IP approach for BPPTW is developed. Third, a spreadsheet is designed to solve the problem using the Solver function. Fourth, a construction heuristic is developed to solve the problem and the solution and computational times are compared.

2.1. Reduction in the Problem Size

The customers were zoned by experts in the company using a geographical mapping technique. Then, local retailers on the same road were clustered into the same group. This diminished the problem size from 690 customers into six problems, each of which had no more than 17 customer groups, resulting in a short computational time. In addition, this approach is more efficient in terms of routing drivers from a 3PL company. The six zones contained different sizes of customer groups (Table 1). For example, in Zone 1, there were 15 groups of customers with a total of 150 customers and demand for 2 ,640 boxes per month. Most zones had 100–150 customers with different levels of demand. Zoning allows a 3PL provider to serve customers more efficiently because the company knows the route for each zone, making it easier to plan delivery.

Table 1 Parameters for customers in each zone

Zone	Total number of customers in each zone	Number of groups of customers in the zone	Total demand for products (boxes/month)
1	150	15	2,640
2	116	11	2,620
3	131	16	1,850
4	103	17	4,220
5	80	13	3,300
6	110	16	1,720
Total	690	88	16,350

2.2. Mathematical Model of BPPTW

The mathematical model of BPPTW in terms of IP was proposed as follows:

Indices and sets

i : customer index, I : set of customers = {1, ..., N}

j : vehicle index, J : set of vehicles = {1, ..., M}

Parameters

M : number of vehicles

N : number of customers

D_i : demand for product for customer i

C_j : capacity of vehicle j

A : maximum number of time window customers per truck

$$T_i : \begin{cases} 1 & \text{if customer } i \text{ has a time constraint} \\ 0 & \text{otherwise} \end{cases}$$

Decision variables

X_{ij} : 1 if delivering the product to customer i by vehicle j; 0 otherwise

Z_j : 1 if vehicle j is used; 0 otherwise

Model formulations

Objective function: minimize $\sum_{j=1}^{M} Z_j$

Subject to:

$$\sum_{j=1}^{M} X_{ij} = 1 \quad \forall\, i = \{1, \dots, N\} \tag{1}$$

$$\sum_{i=1}^{N} D_i X_{ij} = C_j \quad \forall\, j = \{1, \dots, M\} \tag{2}$$

$$\sum_{i=1}^{N} T_i X_{ij} = A \quad \forall\, j = \{1, \dots, M\} \tag{3}$$

$$\sum_{i=1}^{N} X_{ij} = N Z_j \quad \forall\, j = \{1, \dots, M\} \tag{4}$$

Our objective function aims to minimize the total number of trucks outsourced because the company pays a fixed cost per truck. Hence, the minimum number of trucks implies the minimum cost. There are four constraints. First, each group of customers must be allocated to one truck, which implies that the shipment cannot be split, as shown in Equation 1. Second, the total shipment in any truck must be less than its space or capacity, as shown in Equation 2. Equation 3 represents the delivery time constraints, showing that no more than two groups of time window customers (A = 2) will be allocated to the same truck. The last constraint is the if-then constraint in Equation 4, which links two variables together, namely, x_{ij} and y_j. Clearly, the previous constraints contained no y_j. Hence, without this equation, y_j will be zero to minimize the objective function. This implies that whenever a customer order is allocated to a truck, that truck will be used, or the value of y_j must be one. The two variables x_{ij} and y_j are binary.

2.3. Spreadsheet Design

The spreadsheet for the BPPTW model was designed as shown in Figure 1, using the formulas in Tables 2 and 3. The problem was then solved using the Solver function in Excel. The spreadsheet can also be used as a decision support system. This helps allocate the customers to the trucks.

A	B	C	D	E	F	G	H	I	J	K	L	M
1	Customer i	T_i	Demand (D_i)	Truck								
2				1	2	3	4	5	6			
3	1	0	20	1	0	0	0	0	0	1	=	1
4	2	1	30	1	0	0	0	0	0	1	=	1
5	3	0	20	1	0	0	0	0	0	1	=	1
6	4	0	30	0	0	0	0	0	1	1	=	1
7	5	0	20	1	0	0	0	0	0	1	=	[illegible]
8	6	0	30	0	0	0	0	0	1	1	=	1
9	7	0	30	1	0	0	0	0	0	1	=	1
10	8	0	40	1	0	0	0	0	0	1	=	1
11	9	0	30	0	0	0	0	0	1	1	=	1
12	10	0	50	0	0	0	0	0	1	1	=	1
13	11	1	30	0	0	0	0	0	1	1	[illegible]	1
14	12	0	20	1	0	0	0	0	0	1	[illegible]	[illegible]
15	13	1	20	1	0	0	0	0	0	1	=	1
16	14	1	20	0	0	0	0	0	1	1	=	1
17	15	0	10	0	0	0	0	0	1	1	=	1

x_{ij}

Constraint 1

18	16	0	20	1	0	0	0	0	0	1	=	1
19	Total	420	220	220	0	0	0	0	200			
20						<=						
21	C_j			220	220	220	220	220	220			
22	Total T_i	2	0	2	0	0	0	0	2	<=	2	
23			z_j	1	0	0	0	0	1	0	1	
24	sum_i (xij)			9	0	0	0	0	7			
25						<=						
26			N*z_j	16	0	0	0	0	16			

Constraint 2
Constraint 3
Min sum z_j
Constraint 4

Figure 1 Spreadsheet for the BPPTW

Table 2 Description of the spreadsheet

Cell	Meaning	Formula
K3	Total number of trucks used by customer i	=SUM(E3:J3), then drag to cell K4:K18
D19	Total demand from all customers	=SUM(D3:D18)
E19	Total orders delivered by truck j	=SUMPRODUCT($D$3:$D$18,E3:E18), then drag to cell F19:J19
E22	Total number of customer orders with a time window delivered by truck j	=SUMPRODUCT($C$3:$C$18,E3:E18)
E24	Total number of customer orders delivered by truck j	=SUM(E3:E18), then drag to cell F24:J24
E26	Maximum possible number of customers	=$B$18*E23, then drag to cell F26:J26
L23	Total number of trucks used	=SUM(E23:J23)

Table 3 Description of the spreadsheet

Constraint	Formula in Solver
1	K3:K18 ≤ M3:M18
2	SUMPRODUCT($D$3:$D$18,E3:E18) ≤ E21 for truck 1
3	SUMPRODUCT($C$3:$C$18,E3:E18) ≤ L22 for truck 1
4	SUM(E3:E18) ≤ $B$18*E23 for truck 1
Binary	E3:J18, E23:J23 bin

2.4. Construction Heuristic

2.4.1. Definition of notation

G : generation number, Gmax : maximum number of generations = 100

TC = TC_G : total cost of generation i = the outsourcing cost/truck × $\sum_{j=1}^{M} Z_j$

TC^* : optimal total cost

S_1 : customers with no time constraint = {customers with Ti=0}

S_2 : customers with a time constraint = {customers with Ti=1}

k : vehicle index

$k_{max} = \sum_{i=1}^{N} T_i$, $k_{min} = \left\lceil \frac{\sum_{i=1}^{N} T_i}{2} \right\rceil$ implies the smallest integer value that is greater than a summation of Ti/2

C_k : capacity of vehicle k; the remaining notations are the same as in Section 2.2

2.4.2. The construction heuristic algorithm

We observed that the computational time increased as the number of customers increased. We then proposed our heuristic, called the construction heuristic, for solving a particular BPPTW problem. Our algorithm is as follows: First, we determine k_{max} and k_{min}. This will help the algorithm to limit the computational time required to generate a feasible solution. Second, the customers are categorized into two groups, S1 and S2, where S1 represents customers with no time constraint and S2 represents those with a time constraint. Customers in S2 will be allocated as long as the time window constraint is satisfied. The idea is based on the allocation of the most difficult customer orders first. Then, the customers in S1 will be allocated until capacity is reached, at which point the allocation for the current truck is complete. The allocation for a new truck is then started, and the process is repeated until all customer orders are allocated. The cost of this generation is then calculated. The costs are compared, and the solution is selected based on the minimum cost. The process is repeated until the maximum generation is reached, which was set to 100 in our case. Finally, the solutions are sorted in ascending order. The decision maker can select a solution to implement by clicking a dropdown list marked "select solution." We call this the *construction heuristic* because the solution arises from random construction or allocation, while two constraints are considered to generate feasible solutions. The flow chart for the algorithm is shown in Figure 2.

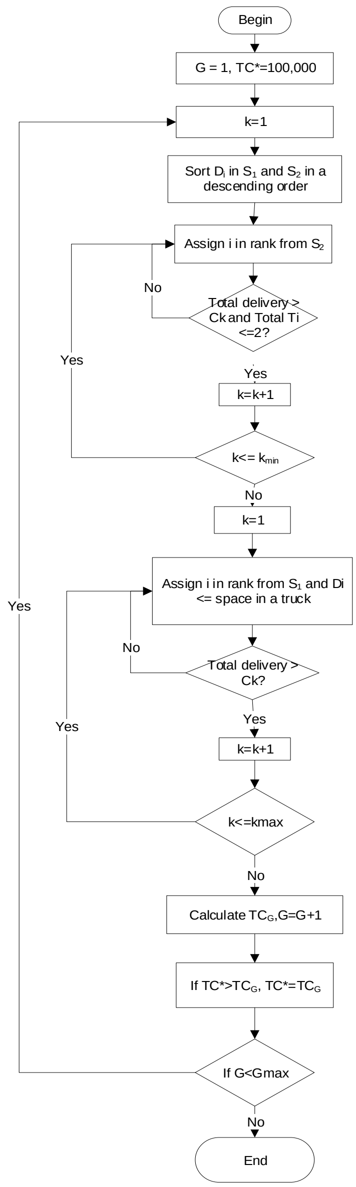

Figure 2 Flow chart for the construction heuristic algorithm

The spreadsheet design and the program employed VBA because of its convenience as a tool for decision support. The design has three main parts—the main program, the input data, and the output data. The main model of the construction heuristic for a BPPTW is shown in Figure 3. The decision maker needs to fill in the demand and time constraints and the numbers of customers and trucks in the spreadsheet; then, the decision maker clicks the "run" button and waits for the solution to be presented in the output sheet.

	RUN	# of customers	# of trucks							Select Solution		
		16	6	Truck id.						1		
	Area	Time Window (T_i)	Demand (D_i)	1	2	3	4	5	6	Total (x_{ik})		
	Using truck or not			1	1	0	0	0	0	2		
	Capacity of Truck			220	220	220	220	220	220	1320		
	# of products delivered		420	220	200	0	0	0	0	0		
				0								
	# of customers of truck k			9	7	0	0	0	0	16		
	# of customers with time window			2	2	0	0	0	0	4	<=	2
1	F1	0	20	0	1	0	0	0	0	1	=	1
2	F2	1	30	0	1	0	0	0	0	1	=	1
3	F3	0	20	1	0	0	0	0	0	1	=	1
4	F4	0	30	1	0	0	0	0	0	1	=	1
5	F5	0	20	1	0	0	0	0	0	1	=	1
6	F6	0	30	1	0	0	0	0	0	1	=	1
7	F7	0	30	0	1	0	0	0	0	1	=	1
8	F8	0	40	1	0	0	0	0	0	1	=	1
9	F9	0	30	0	1	0	0	0	0	1	=	1
10	F10	0	50	0	1	0	0	0	0	1	=	1
11	F11	1	30	1	0	0	0	0	0	1	=	1
12	F12	0	20	1	0	0	0	0	0	1	=	1
13	F13	1	20	1	0	0	0	0	0	1	=	1
14	F14	1	20	0	1	0	0	0	0	1	=	1
15	F15	0	10	1	0	0	0	0	0	1	=	1
16	F16	0	20	0	1	0	0	0	0	1	=	1

Figure 3 Main model of the construction heuristic for a BPPTW

3. Results and Discussion

3.1. Construction Heuristic Results

The output sheet gives the solutions of the construction heuristic for a BPPTW, as shown in Figure 4. The solutions are presented in increasing order of cost, and the decision maker can select which solution will be implemented. The solution to the current problem using real data in six zones is shown in Table 4. The next section compares the solutions obtained from the three methods.

Gen	Number of trucks	1	2	3	4	5	6	SUM
1	2	220	200	0	0	0	0	420
2	2	200	220	0	0	0	0	420
3	2	200	220	0	0	0	0	420
4	2	210	210	0	0	0	0	420
5	2	210	210	0	0	0	0	420
6	2	220	200	0	0	0	0	420
7	2	210	210	0	0	0	0	420
8	2	200	220	0	0	0	0	420

9	2	220	200	0	0	0	0	420
10	2	210	210	0	0	0	0	420
11	2	210	210	0	0	0	0	420
12	2	220	200	0	0	0	0	420
13	2	200	220	0	0	0	0	420
14	2	210	210	0	0	0	0	420
15	2	220	200	0	0	0	0	420
16	2	200	220	0	0	0	0	420
17	2	220	200	0	0	0	0	420
18	2	220	200	0	0	0	0	420
19	2	220	200	0	0	0	0	420
20	2	220	200	0	0	0	0	420

Figure 4 Output sheet presenting the solutions from the construction heuristic for a BPPTW

Table 4 Solution found using the construction heuristic

Zone	# of trips per year	Transportation cost (baht/year)
1	156	210,600
2	156	241,800
3	156	241,800
4	260	429,000
5	208	322,400
6	104	171,600
Total	1,040	1,617,200

3.2. Comparison between IP and the Construction Heuristic using Real Data

In this section, we compare the solutions for the real data using the three different methods—the existing method, the IP approach, and the construction heuristic; the results are shown in Table 5. The IP approach and the construction heuristic perform well for the dataset. The number of shipments per year is reduced from 1,352 to 1,040 trips, a decrease of 23.07%, and the transportation cost can be reduced by 489,450 baht per year, or 23.23%. In addition, overtime is not required. This enables the staff to schedule punctual deliveries, and there is no need to reschedule because there is no delay. However, there is a limitation related to the problem size. In summary, the company could reduce outsourcing costs by using both the IP approach and the construction heuristic. However, when the problem size becomes larger, using IP may take too long to solve the problem, or the method may be unable to find the solution, which is the same concern that Ongkunaruk and Ongcunaruk (2015) raised. Hence, the construction heuristic is an alternative method to solve the problem in real time.

Table 5 Comparison of three methods

KPIs	Existing Method	IP	Construction Heuristic	% Improvement
# of trips/year	1,352	1,040	1,040	23.07%
Transportation cost (baht/year)	2,106,650	1,617,200	1,617,200	23.23%
OT (hrs/day)	4	-	-	
Alternative solutions	×	×	√	

3.3. Comparison between IP and the Construction Heuristic using Generated Data

To examine the case of future use in which the number of customers has increased, we generated several similar datasets by varying the number of customers and compared the computation time between the IP approach and the construction heuristic, as shown in Table 6. The results showed that the Solver could not handle problems with more than 32 customers, although the Solver performed quite well in terms of computational time for small problems. For large problems, the construction heuristic outperformed the IP approach. In addition, our heuristic approach provides more options for feasible solutions for the decision maker. In summary, the construction heuristic could be used as a decision support tool by the company in the future. It should be noted that these results may differ if other computers are used (based on CPU performance).

Table 6 Comparison of computation time between the IP and the construction heuristic

# of customers	Computation time (seconds)	
	IP	Construction Heuristic
16	3	12
17	4	17
30	345*	18
32	NA**	30
50	NA***	43
100	NA***	71

*The problem could not be solved in less time than this; **The Solver could not find a feasible solution;
***The IP approach could not find a solution because there were too many variables when the number of customers was greater than 32

4. Conclusions

This study improved the method of solving the BPPTW for a case study company by addressing the limitation of the IP approach when solving large problems. We proposed the construction heuristic to find alternative solutions to improve upon IP. The algorithm was designed to prioritize allocation for customers with time constraints, and the program was written in VBA in Excel. Our heuristic can solve a large problem within a short time, whereas the Solver cannot be used when the number of customers exceeds 32. The Solver takes a longer time than our heuristic when the problem size increases. In addition, the construction heuristic is designed to be user-friendly. In summary, the construction heuristic can be used as a decision support tool for the company, resulting in reduced computational time and lower human error. In the future, the company will be able to cooperate with the 3PL provider to solve the vehicle routing problem with time window constraints and find global optimum solutions for the company and the 3PL. Then, such heuristics as genetic algorithms can be proposed to solve the problem (Chen et al., 2016; Ongkunaruk et al., 2016).

Acknowledgements

The authors would like to thank the case company, which kindly provided information for this research. We are also grateful to the anonymous reviewers, who made valuable recommendations to improve our manuscript.

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