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Maximal Covering Problem Model for Determination of Fire Station Location

(A Case Study)

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***Abstract*—This research aims to determine the optimal location and number of fire stations in Situbondo Regency by considering the travel time, development cost, and track record of fire incidents using the maximal-covering problem model. Furthermore, the model is solved using the branch and bound method using GAMS, optimization software. The objective function is to maximize Z, which is the coverage of all the districts in Situbondo with capacity, the maximum number in the fire management area, and the maximum number in each district constraints. The solution of the optimization model that is the optimal location of the fire station in Situbondo is locating in Besuki, Mlandingan, Panarukan, Panji, and Jangkar districts, each with type C fire station with the total value of Z is 12. Currently, the location of the fire station is in 3 districts, namely Panji (type A), Asembagus (type C), and Besuki (type C), then the district coverage (Z) is 11. The coverage value of the new fire stations in the optimization model is greater than the current coverage value so that the solution is more optimal than the current condition.**

Keywords*—maximal covering problem model, determining fire station location, multi-objective model

I. Introduction

Recently, the number of fire incidents in Situbondo Regency is increasing as reported by newspapers and online news. According to the information from the Fire and Rescue Unit, over the past five years, the fire incidents is increased rapidly. The incidents have made the comfort and safety of Situbondo community disturbed. The Situbondo government through the Fire and Rescue Unit has the responsibility for the comfort and safety of the Situbondo community. The Fire and Rescue Unit is located at Madura Street Number 17 Panji District, Raya Asembagus Street Number 79 Asembagus District, and Raya Situbondo Street Number 59 Besuki District. There are 7 units of fire trucks (2 unit at Panji, 1 unit at Besuki, 1 unit at Asembagus) and 75 personnel (34 people at Panji, 19 people at Besuki, and 22 at Asembagus). Fire and Rescue Unit trying to serve the community optimally. However, several constraints can obstruct the process of overcoming of fire incidents. During this time the constraints were occurring not only caused by less equipment but also response time to reach the location of the fire incidents. In the future, Situbondo government will build new fire stations to reach areas that yet or difficult to reach by Fire and Rescue Unit personnel.

The addition of new stations needs to be prepared carefully in to reach remote areas. Therefore, an appropriate method is needed to determine the location and the number of new strategic fire stations. One of the methods that can be used is linear programming. Linear programming is one of the mathematics methods to optimize the objective function with the limitations called the constraints. In the linear programming, there is the maximum covering problem model which can be used to model the determination of fire station's location.

There have been several previous studies that discussed the selection of fire station locations with linear programming. Araz, et al discussed the issue of selecting vehicle locations for emergency services modelled using a multi-objective maximal covering location model [1]. Chevalier, et al illustrate operational tools for determining location, equipment allocation, employee preparation, response time, and so on that can be used for the plan of reorganizing the fire station [2]. Jasriadi, Iriana, and Djuniati analysed the location and number of Pekanbaru city fire stations using GIS (Geographic Information System) [3].

Bahri constructed a model of the fire station [4]. The model is used to determine the minimum number of fire stations in Padang considering the travel time from the fire station to the fire incident location [4]. Idayani uses a set covering problem model to determine the location and number of fire stations to minimize the cost of building a fire station [5]. However, it has not been studied whether the specified location and number of fire stations can reach the entire fire management area.

Therefore, this study determines the location of fire stations that can reach the entire fire management area considering the weight of each district, travel time, capacity, and number of

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desired posts in Situbondo. Problems modelled using maximal covering problem model [6] with a maximum number of 6 fire stations [5]. Furthermore, the model is completed using the branch and bound method so that an optimal solution is found. In completing the model is used GAMS, an optimization software. Solutions obtained from this research compared to solutions obtained without the use of optimization models to know that the solution offered is optimal.

II. PRELIMINARIES

A. Maximal Covering Problem Model

The maximal covering problem model aims to maximize the coverage of districts by assuming that the number of fire stations to be opened is limited to achieve 100% fulfilment [7]. The maximal covering problem model is formulated as follows [6].

Objective function:

$$Z = \sum_{i \in I} w_i y_i \tag{1}$$

Constraints:

$$\sum_{j \in N_i} \sum_{k \in K} r_k x_{jk} \geq w_i y_i, \quad \forall i \in I \tag{2}$$

$$\sum_{j \in J} \sum_{k \in K} x_{jk} \leq p \tag{3}$$

$$\sum_{k \in K} x_{jk} \leq 1, \quad \forall j \in J \tag{4}$$

$$x_{jk} \in \{0,1\} \quad \forall j \in J, \forall k \in K \tag{5}$$

$$y_i \in \{0,1\} \quad \forall i \in I \tag{6}$$

Where:

I = set of districts $i \in \{1,2, \ldots ,17\}$;

J = set of candidate fire station locations (i.e., districts).

K = set of fire station types, $k\{A, B, C\}$

w_i = weight of district i

r_k = capacity of a fire station of type k per year.

d_{ij} = travel time between districts i and j;

S = standard time for a fire station site at a district j to be eligible to serve district i ($S = 5$ minutes of travel time in this research).

N_i = set of districts j within the standard time S of district i, $N_i = \{d_{ij} \leq S\}$;

P = number of fire stations to be opened (6 in this research)

x_{jk} = binary decision variable (1 if a fire station is opened in district j, 0 otherwise)

y_i = binary decision variable (1 if a fire station is opened in district j and is eligible to serve district i, 0 otherwise)

B. Branch and Bound Method

The branch and bound algorithm were developed by A. Land and G. Doig in 1960 for the mixed and pure integer linear programming problem. Then in 1965, E. Reply developed an additional algorithm for solving the integer linear programming with pure binary variable (0 or 1). The computation of additional algorithms is so simple (mostly sums and fractions) that it was originally thought to be a breakthrough in general integer linear programming solution but failed to produce the desired computational benefits. Besides, the algorithm, which initially had no relationship with the branch and bound technique, is a special case of the general Land and Doig algorithm [8].

The branch and bound method are a method for determining solutions to integer linear programming problems, including set covering problem and maximal covering problem. An important principle in this method is the number of feasible solution set can be divided into subsets of smaller solution. Then, the subsets are systematically evaluated until the best solution is found.

III. RESULTS AND DISCUSSIONS

A. Fire Station Location Determination Model

1) Objective function. The objective function (1) based on the goal to maximize the coverage of service demand in each district in the establishment of new fire stations. The objective function has constant w_i and variable y_i.

The constant w_i is the weight assigned to each district i that denote the set of districts in the fire management area of Situbondo. In this research, the weight is determined by considering population density. The higher the density of population, the higher the weight.

Besuki District is the most populous district whereas Banyuputih District has the smallest density population. Data of population and density of the population of each district is obtained from the archives of BPS-Statistics of Situbondo Regency. The highest population is in Panji District, while the smallest population is in Banyuputih [9].

The weight determination also considers the districts strategic value. A district which is the centre of Regency has larger weight than the others. The weight of each district is: $w_4 = w_{10} = w_{12} = 3$, $w_5 = w_6 = w_9 = w_{11} = w_{13} = w_{15} = w_{16} = 2$, and 1 otherwise.

The variable y_i is a binary decision variable, 1 if a fire station is opened in district j and eligible to serve district i and 0 otherwise. The i index denotes the set of districts in fire management area. There are 17 districts, so $i = 1,2,3, \ldots 17$. The variables y_i can be written as follows.

y_1 = Sumbermalang, y_7 = Bungatan, y_{13} = Kapongan

y_2 = Jatibanteng, y_8 = Kendit, y_{14} = Arjasa

y_3 = Banyuglugur, y_9 = Panarukan, y_{15} = Jangkar

y_4 = Besuki*, y_{10} = Situbondo, y_{16} = Asembagus*

y_5 = Suboh, y_{11} = Mangaran, y_{17} = Banyuputih

y_6 = Mlandingan, y_{12} = Panji*

where *) is the location of the current fire station.

Based on the weight w_i, the objective function (1) becomes

$$Z = y_1 + y_2 + y_3 + 3y_4 + 2y_5 + 2y_6 + y_7 + y_8 + 2y_9 + 3y_{10} + 2y_{11} + 3y_{12} + 2y_{13} + y_{14} + 2y_{15} + 2y_{16} + y_{17} \quad (7)$$

2) The first constraint: The right type. The right type of constraint (2) ensure that the type of selected fire station is appropriate to respond to the fire incident in each district. The left side of the constraint consists of a constant r_k (the capacity of the fire station) and variable x_{jk}. The right side of the constraint consists of weight w_i and variable y_i.

Bagir and Buchori explained that IFCAA (International Fire Chiefs Association of Asia), an international institution of fire chiefs in Asia, said the standard services of a fire station is 30,000 inhabitants, while a fire truck and 25 personnel of firefighters for 10,000 residents with a response time is 15 minutes [10]. However, the standard cannot be generalized due to different density population. Especially if the fire incidents not only occur in settlements but also in land and forest.

A lot of things can affect how much the fire station capacity such as distance, the level of fire potential, the population characteristics, etc. [10]. The capacity of each fire station type obtained from Fire and Rescue Unit information by estimating how many incidents that can be handled in one year with considering the number of fire trucks and personnel. A fire incident in Situbondo requires 1-5 units of fire trucks. The requirement for a fire truck cannot be estimated with certainty because it depends on the fire. On average, to handle a fire incident requires 3 fire trucks. Besides, the number of personnel also affects the handling of a fire incident. The capacity of fire incident is $r_A = 200, r_B = 100,$ and $r_C = 50$.

The variable x_{jk} is formed by considering the average travel time needed to reach the location of a fire incident. If the average of travel time is less than 15 minutes, then the new fire station is possible to be opened in district j. It means that district j is the candidate location of a new fire station. So, the value of binary decision variable is $x_{jk} = 1$ and otherwise $x_{jk} = 0$ (Table 1).

TABLE I. BINARY DECISION VARIABLE x_{jk}

	x_{1k}	x_{2k}	x_{3k}	x_{4k}	x_{5k}	x_{6k}	x_{7k}	x_{8k}	x_{9k}	x_{10k}	x_{11k}	x_{12k}	x_{13k}	x_{14k}	x_{15k}	x_{16k}	x_{17k}
x_{1k}	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
x_{2k}	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
x_{3k}	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
x_{4k}	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
x_{5k}	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
x_{6k}	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
x_{7k}	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
x_{8k}	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0
x_{9k}	0	0	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0
x_{10k}	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
x_{11k}	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
x_{12k}	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
x_{13k}	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
x_{14k}	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0
x_{15k}	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
x_{16k}	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
x_{17k}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

So, the constrains are:

$$200x_{1A}+100x_{1B}+50x_{1C}+200x_{2A}+100x_{2B}+50x_{2C}+200x_{3A}+100x_{3B}+50x_{3C}+200x_{4A}+100x_{4B}+50x_{4C}+200x_{5A}+100x_{5B}+50x_{5C}+200x_{6A}+100x_{6B}+50x_{6C}+200x_{7A}+100x_{7B}+50x_{7C}\geq y_1 \quad (8)$$

$$200x_{1A}+100x_{1B}+50x_{1C}+200x_{2A}+100x_{2B}+50x_{2C}+200x_{3A}+100x_{3B}+50x_{3C}+200x_{4A}+100x_{4B}+50x_{4C}+200x_{5A}+100x_{5B}+50x_{5C}+200x_{6A}+100x_{6B}+50x_{6C}+200x_{7A}+100x_{7B}+50x_{7C}+200x_{8A}+100x_{8B}+50x_{8C}\geq y_2 \quad (9)$$

$$\vdots$$

$$200x_{13A}+100x_{13B}+50x_{13C}+200x_{14A}+100x_{14B}+50x_{14C}+200x_{15A}+100x_{15B}+50x_{15C}+200x_{16A}+100x_{16B}+50x_{16C}+200x_{17A}+100x_{17B}+50x_{17C}\geq y_{17} \quad (10)$$

3) The second constraint: The maximal number of fire stations. The second constraint is the number of fire stations that is not more than the predetermined limit. The limit of the number of fire stations obtained from the solution of the set covering problems model as many as 6 fire stations [5]. So, the constraints (3) become.

$$x_{1A}+x_{1B}+x_{1C}+x_{2A}+x_{2B}+x_{2C}+x_{3A}+x_{3B}+x_{3C}+x_{4A}+x_{4B}+x_{4C}+x_{5A}+x_{5B}+x_{5C}+x_{6A}+x_{6B}+x_{6C}+x_{7A}+x_{7B}+x_{7C}+x_{8A}+x_{8B}+x_{8C}+x_{9A}+x_{9B}+x_{9C}+x_{10A}+x_{10B}+x_{10C}+x_{11A}+x_{11B}+x_{11C}+x_{12A}+x_{12B}+x_{12C}+x_{13A}+x_{13B}+x_{13C}+x_{14A}+x_{14B}+x_{14C}+x_{15A}+x_{15B}+x_{15C}+x_{16A}+x_{16B}+x_{16C}+x_{17A}+x_{17B}+x_{17C}\leq 6 \quad (25)$$

4) The third constraint: One fire station in a district. The number of fire stations constraint represents the constraint (4). This constraint ensures that the number of opened fire stations is only one in each district. So, the constraints (4) can be described into 17 constraints.

$$x_{1A}+x_{1B}+x_{1C}\leq 1 \quad (26)$$

$$x_{2A}+x_{2B}+x_{2C}\leq 1 \quad (27)$$

$$\vdots$$

$$x_{17A}+x_{17B}+x_{17C}\leq 1 \quad (42)$$

5) The optimal solution of fire station location determination model. The solution of fire station location determination model with the branch and bound method obtained by GAMS software. GAMS is a high-level modelling system for optimization programming that provides the programming language compiler and various related solver. The modelling language of GAMS allows the model maker to translate real-world optimization problems to the computer code fast [11].

According to Rosenthal [12], GAMS provides a high-level language to represent large and complex models. GAMS allows model specification can be changed easily and safely, using the ambiguous statement of the algebra relationship. Besides, the model description has independent solution algorithm.

The GAMS output shows the solution of the maximum covering problem model that maximizes the objective function (7) with constraints (8) - (42) is $x_{4C}, x_{6C}, x_{9C}, x_{12C}$, and x_{15C} that each is equal to 1 with Z value equal to 12. Based on these results, the optimal location of fire stations in Situbondo is in Besuki, Mlandingan, Panarukan, Panji, and Jangkar, each of them has type C fire station.

Currently, the location of fire stations in Situbondo is in Panji (type A), Asembagus (type C), and Besuki (type C). Then the coverage value Z is 11. By comparing the value of Z (coverage), the solution offered by the maximal covering problem model is more optimal than the current condition because the value of Z of maximal covering problem model is greater than the value of Z of the current condition.

IV. Conclusion

The determination of the location and the number of fire stations can be solved with the maximal covering problem model. The maximal covering problem model completes the set covering problem results by adding weight to the populous and important districts.

In the next research, the determination of the weight may consider tourism spots. Besides, the model can be added objective functions so that it becomes a multi-objective model. Some constraints also can be added to the model.

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