Condition-Based Building Maintenance Strategy Selection Using Constraint Programming

Shu-Shun Liu and Gilang Ramadhan

Department of Civil and Construction Engineering, National Yunlin University of Science and Technology, No 123,Section 3, University Road, Douliu, Yunlin, 640, Taiwan ROC
E-mail: liuss@yuntech.edu.tw g.ramadhan3103@gmail.com

Abstract-

Naturally, buildings will deteriorate during its life cycle. On the other hand, sustainability of building condition is the main objective of providing service for users. Therefore, building maintenance management should be a priority to achieve that objective. In Indonesia, there are many public buildings with different conditions and some of them are not in optimal conditions demanding urgent maintenance treatment. In addition, limited budget and absence of building maintenance decision-making tool are among factors causing unmanaged maintenance activities. Moreover, agencies must allocate maintenance budget and prioritize buildings maintenance manually. This paper proposes an optimization mathematical model which adopts Constraint Programming (CP) formulation to assist in selecting the most cost-effective strategy for particular building and determining budget allocation each year. CP is famous on its flexibility to problem declaration that makes scenario analysis conduct effectively. This CP-based model subjects to budget constraint and required condition level. In this case, budget, maintenance strategy options, building deterioration rate, time period, and minimum acceptable building condition are set. There are four maintenance strategy options available, Light Repair, Rehabilitation, Renovation, and Restoration which have different improvement impact for each strategy. Therefore, a case study is conducted to implement the model which involves 15 buildings in a 10-year time of period and two scenarios are presented in this proposed model. The result shows that the two scenarios allocate annual maintenance budget differently depending on diversities of planner management goals.

Keywords-

Building Maintenance, Condition-Based Maintenance, Maintenance Strategy, Optimization, Constraint Programming

1 Introduction

Building is one of important assets of an institution or organization. Different institutions have different types of building with various functions. Some of the buildings are offices, schools, sport centres, convention halls, and many more. These kinds of building aim to facilitate activities of owners and users. To give an optimal service, a building should be in a good condition. However, condition level of buildings may decline during its life cycle. Ultimately, a building needs a proper maintenance activity strategy to ensure its level of condition is within an acceptable degree.

Au-Yong et al. [1] stated that building maintenance is vital in ensuring the building's sustainability. Maintenance can preserve building's condition in receivable state of service. Maintenance is defined as a combination actions carried out to retain an item in, or restore it to, an acceptable condition [2][3]. Moreover, maintenance activities can lengthen age of buildings in providing service for owner and users.

However, in some parts of Indonesia, building maintenance has not been taken into account. Owner who have many buildings, in this case government, still do not consider maintaining building as an important issue. Due to limited budget and a huge number of buildings with different level of condition, building maintenance program is planned as needs arise. Consequently, many buildings are in bad condition and cannot provide optimal service to users. In other cases, some buildings are maintained but due to lack of maintenance management and planning, the maintenance requires high cost and inappropriate maintenance action is chosen.

This problem needs a solution to prevent worse building condition and higher maintenance cost spent. Some strategies can be implemented to overcome this problem. Condition-based maintenance can be applied to overcome the problem. Condition-based maintenance aims to minimize the total maintenance cost by collecting and gathering the condition data of the building systems, especially the critical components [1]. This maintenance strategy can determine the most suitable maintenance action for certain building in order to reach optimal condition and reduce cost of maintenance.

By applying constraint programming approach, this study aims to provide a simple decision-making tool to help buildings owners managing their buildings maintenance program. The proposed model is a strategy selection program using constraint programming. The objective of this model is to select the most cost-effective maintenance action for particular building in certain year to achieve acceptable level of condition for all buildings at the end of a maintenance plan period.

2 Literature Review

Maintenance optimization related topics are widely studied by some researchers although it is not directly linked with building maintenance. Particularly, the Markov prediction model is widely used to predict future pavement maintenance due to its ability to integrate rehabilitation and pavement deterioration rates in a single transition probability matrix [4]. Abaza et al [4] implemented a Markov model to predict future pavement performance and developed non-linear optimization method to establish optimum pavement condition throughout the network subject to budget constraints.

Another method used in network-level optimization topic is goal programming. This approach is favoured due to its strength in considering problem encompassing conflicting objectives with different degrees of importance [5]. Previous research conducted by Ravirala and Grivas [5] presented that goal programming is beneficial in obtaining conflicting objectives simultaneously.

Meanwhile, constraint programming is also commonly used to solve optimization problem on maintenance strategy. One of the previous works was conducted by Badr and Brown [6]. They proposed a cost-based reasoning and constraint programming model on building maintenance scheduling. Additionally, they introduced a heuristic ModReg model to guide the search process towards an optimal schedule.

Constraint programming is widely applied to deal with scheduling and planning problems in different areas. One of the examples is Chan and Hu [7] who employed constraint programming to propose precast production scheduling model that incorporates the key constraints and objectives considered by production scheduler. Another work was established by Brailsford [8] who discussed and compared the advantages of constraint programming method for solving constraint satisfaction problems, such as timetabling and roistering problem. Rodriguez [9] proposed a constraint programming model for the routing and scheduling of trains running through a junction to assist operator in changing train routes or order to avoid conflicts and delays.

Furthermore, Liu and Wang [10] presented an optimization model using constraint programming approach for project selection and scheduling problems with time-dependent resource constraint. In another work, constraint programming was also applied by Liu and Wang [11] to propose a profit optimization model for multi-project scheduling problems by considering cash flow and the financial requirements of contractor working in a multi-project environment.

3 Conceptual Model

This study aims to develop a decision-making tool in selecting building maintenance strategy. Constraint programming is used because it is flexible in problem declaration that makes scenario analysis conducted effectively. Constraint programming is not restricted to the linear equations, but allowing the users to change contents for achieving required model [12].

Furthermore, the proposed model intends to find the most optimal solution choosing cost-effective maintenance strategy for all buildings using binary variable, where 1 means a strategy is implemented and 0 means otherwise. Under set of constraints the model will choose which strategy is the most effective for each building and when the strategy is implemented.

Subsequently, two scenarios will be conducted. Scenario 1 is intended to achieve the minimum acceptable condition for all buildings in every year. Meanwhile, Scenario 2 will require all buildings to reach at least the minimum acceptable condition at the end of a maintenance plan period.

Owners often have many buildings with different level of condition. It is important to determine each category of buildings condition level. The data of buildings condition level will be very useful in choosing the most appropriate strategy for a certain building. The model will consider the condition of buildings and cost of each strategy to propose the best maintenance activity.

There are five levels of building conditions. They are Very Good, Good, Average, Poor, and Bad. These criteria will be used to consider which maintenance action will be taken for a particular building. In addition, the five states of buildings condition are transformed into an index modified after Uzarski work [13] to simplify the calculation process in the model. The highest point of building condition level, which is very good, is 95 and the lowest point of the condition level of bad condition is 35. The objective is to upgrade buildings condition to achieve acceptable condition level which is good condition. Fifteen (15) buildings are employed and details of these buildings initial condition are presented in Table 1.

Table 1. Buildings Initial Condition

Building	Level of Condition	Condition Index
Building A	Good	78
Building B	Poor	53
Building C	Very Good	89
Building D	Bad	38
Building E	Average	65
Building F	Good	77
Building G	Poor	50
Building H	Good	85
Building I	Bad	44
Building J	Average	70
Building K	Good	80
Building L	Good	74
Building M	Very Good	87
Building N	Bad	42
Building O	Good	75

Building deterioration rate or building degradation level is also very essential in determining the most effective maintenance strategy. Building deterioration rate used in this study is adopted from the regulation of Ministry of Public Work of Indonesia [15]. The regulation states that degradation of building condition is 2% each year [15]. The data of the initial condition in this study is established deterministically and for the following years, 2% degradation every year is used in a 10-year maintenance plan period.

Furthermore, there are four types of maintenance strategy to upgrade buildings to acceptable condition level proposed in this model. The strategies are Light Repair, Rehabilitation, Renovation, and Restoration. Each strategy has different impact in improving building condition and upgrading to higher level of condition. The detail of the four strategies and its relationship with the five building conditions are shown in Figure 1.

4 Model Formulation

This section presents an overview of a constraint programming model formulation. The model aims to find the least budget spent of maintenance strategies applied and satisfy all constraints. The variables, parameters, sets, constraints, and objective function are presented as follows.

$$Min \sum_{i=1}^{i}\sum_{j=1}^{j}\sum_{k=1}^{k} C_{ik} \cdot S_{ijk} \tag{1}$$

s.t.

$$\sum_{i=1}^{i}\sum_{k=1}^{k} C_{ik} \cdot S_{ijk} \leq F_j, \forall j \in Y \tag{2}$$

$$\sum_{k=1}^{k} S_{ijk} \leq 1, \forall i \in B, \forall j \in Y \tag{3}$$

$$\sum_{k=1}^{k} S_{ijk} \cdot I_k + CB_{ij} = CA_{ij}, \forall i \in B, \forall j \in Y \tag{4}$$

$$CB_{ij} = D_i, \forall i \in B, j = 1 \tag{5}$$

$$CB_{ij+1} = CA_{ij} \cdot 0.98, \forall i \in B, \forall j \in Ymin \tag{6}$$

$$CA_{ij} \geq A, \forall i \in B, \forall j \in Y \tag{7}$$

$$CA_{ij} \geq A, \forall i \in B, j = 10 \tag{8}$$

$$CA_{ij} \leq M, \forall i \in B, \forall j \in Y \tag{9}$$

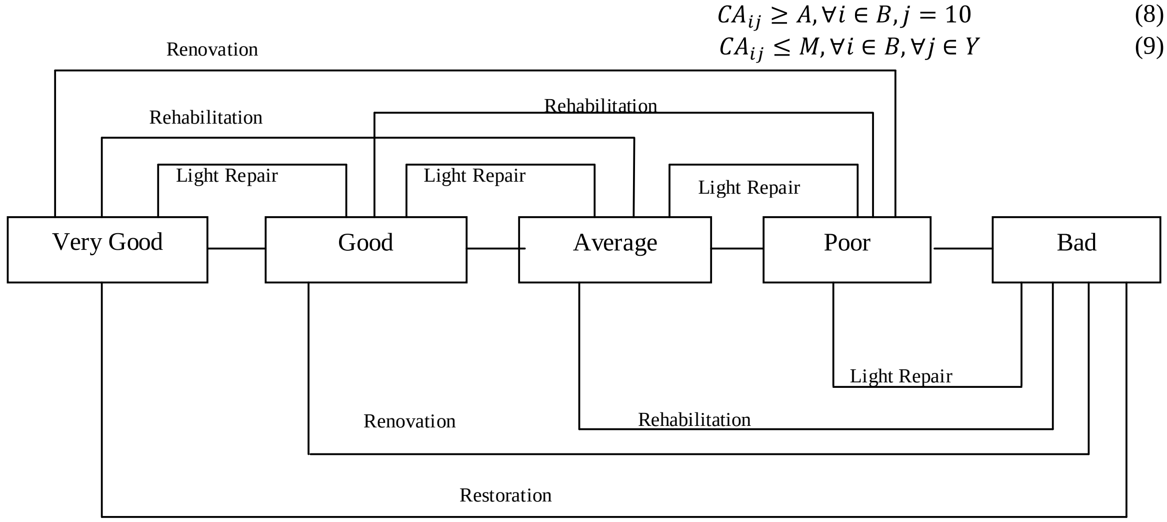

Figure 1. Building Condition Levels and Building Maintenance Strategies Modified After de la Garza et al. [14]

The objective function in equation (1) enables cost of each strategy to prioritize the most cost-effective strategy for each building in certain year to minimize total budget spent on all maintenance strategies. C is a parameter of cost of strategy k of building i. Then, S represents binary variable for strategy selection, corresponding to maintenance strategy k of building i in year j, whether certain strategy is chosen ($S_{ijk}=1$) or not ($S_{ijk}=0$).

Equation (2) is constraint for the annual maintenance budget. F_j in this equation denotes amount of money in j year. Money spent on certain strategy of all buildings in a year must be less than or equal to maintenance budget in that year where B is set of buildings and Y is for years. Equation (3) restricts to choose only one strategy for particular building in a year or not to do any maintenance activity at all. Equation (4) aims to present information about the condition after S_{ijk} maintenance strategy is applied to building i in one year period (year j). I_k in this constraint indicates improvement of strategy k. Meanwhile, CB_{ij} means condition of building i in year j before a maintenance strategy is implemented and CA_{ij} describes condition of building i in year j after a maintenance strategy is employed.

Equation (5) states the condition of buildings in the beginning of the first year (base line) where D_i represents the damage of building i. Equation (6) shows the degradation of buildings condition in every year. The degradation rate of buildings conditions is 2% per year, so that, CA_{ij} is multiplied by 0.98 to find value of building condition in the beginning of the next year (CB_{ij+1}). Equation (7) requires all buildings must be greater than or at least equal to minimum acceptable level of buildings condition in every year and in this case the minimum level of buildings condition (A) is 75 and this constraint will be used in Scenario 1 but will be omitted in Scenario 2 due to different objective. Otherwise, equation (8) demands all building to achieve the minimum acceptable condition at least at the end of the period and this constraint will generated in Scenario 2 but will not be involved in Scenario 1. Equation (9) limits the condition of all buildings must be less than or equal to maximum building condition (M) which is 95.

ILOG OPL Studio software is used to run the model and to find the optimal solution. ILOG is very convenient software to run an optimization model because the model can be written with a simple language and notation. The software enables users to separate the model with the data, so that the same model can easily be used with different data.

5 Case Study and Result

The buildings involved in this study have four options of maintenance treatment with different cost for each building. The proposed model will attempt to find the most cost-effective maintenance strategy of every building and to achieve the minimum acceptable level of condition at the end of time period.

The result of Scenario 1 is presented on Table 2. The table shows maintenance action chosen for each building and the time of maintenance treatment implementation. Building B, Building D, Building E, Building G, Building I, Building J, Building L, and Building N are maintained with different maintenance strategy in the first year. This is because those building have lower condition level than the minimum acceptable condition level. Subsequently, almost all of those buildings (except Building L) will have to be repaired for the second time to upgrade the condition because in the maintenance plan period, the buildings deteriorate to below the minimum acceptable condition level.

Table 2. Result of Scenario 1

Building	Maintenance Strategy[a)]	Year of Maintenance[a)]
Building A	Light Repair	4th
Building B	Rehabilitation	1st
	Light Repair	7th
Building C	Light Repair	10th
Building D	Renovation	1st
	Light Repair	3rd
Building E	Light Repair	1st
	Light Repair	8th
Building F	Light Repair	3rd
Building G	Renovation	1st
Building H	Light Repair	8th
Building I	Renovation	1st
	Light Repair	7th
Building J	Light Repair	1st
	Light Repair	10th
Building K	Light Repair	5th
Building L	Light Repair	1st
Building M	Light Repair	9th
Building N	Renovation	1st
	Light Repair	6th
Building O	Light Repair	2nd

[a)]The results are derived from the model

For the rest of the buildings, they are treated in different time as their initial conditions are different. Then, most of these buildings are maintained with same maintenance activity which is Light Repair. This condition happens because Light Repair maintenance is the cheapest maintenance action and when the building condition drops to below the minimum acceptable level of condition, the maintenance strategy will improve buildings' condition effectively.

Regarding the building condition level, result of Scenario 1 is shown in Figure 2. From 5 sample buildings that represent 5 different initial conditions, Average, Poor, and Bad initial condition buildings are directly maintained to reach minimum acceptable condition and these building are maintained twice. In addition, the buildings will be at the minimum condition until the end of the period. Meanwhile, buildings with Very Good and Good condition are maintained after deteriorating to below 75.

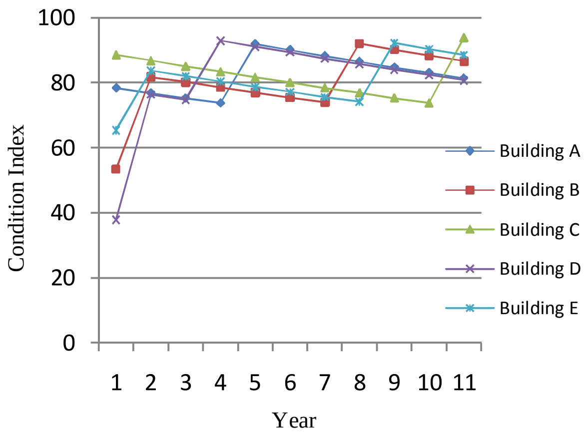

Figure 2 Buildings Condition Performance of Five Buildings in Scenario 1

The money spent each year for maintenance activities of Scenario 1 is shown in Figure 3. Due to so many buildings need to be maintained in the first year, Scenario 1 requires high cost in the first year to conduct some maintenance activities for some buildings. On the other hand, the maintenance spending in the following years will be very little because there are few buildings will deteriorate to below the standard each year. The total budget spent in 10 years in this scenario is approximately 8.1 billion rupiahs.

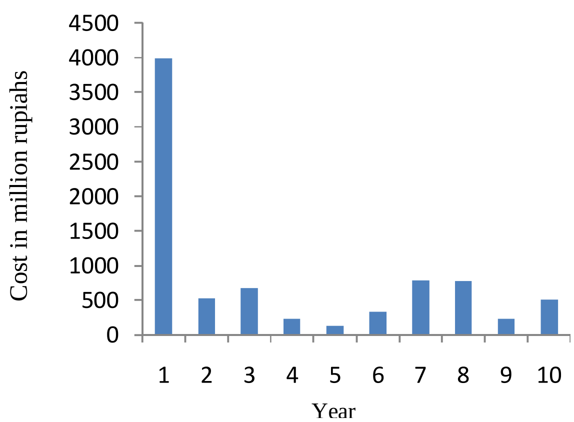

Figure 3. Yearly Budget Spent in Scenario 1

In Scenario 2, the model is modified by removing equation (7) and adding equation (8). This scenario aims to require all buildings must be greater than the minimum acceptable condition at the end of the period. However, this scenario does not consider the condition of the buildings in every year. Table 3 shows that most of the buildings are maintained in the last years of the period (8th, 9th and 10th year). In addition, the Light Repair strategy still becomes the most favourable maintenance strategy, but there are only two buildings getting the second maintenance treatment in this scenario which are Building D and Building N.

Table 3. Result of Scenario 2

Building	Maintenance Strategy [a)]	Year of Maintenance[a)]
Building A	Light Repair	4th
Building B	Renovation	7th
Building C	Light Repair	10th
Building D	Rehabilitation	5th
	Light Repair	7th
Building E	Rehabilitation	4th
Building F	Light Repair	3rd
Building G	Renovation	10th
Building H	Light Repair	8th
Building I	Renovation	10th
Building J	Light Repair	10th
Building K	Light Repair	5th
Building L	Light Repair	10th
Building M	Light Repair	9th
Building N	Light Repair	8th
	Rehabilitation	9th
Building O	Light Repair	3rd

[a)] The results are derived from the model

In terms of buildings condition, Scenario 2 does not consider the buildings condition performance in each year. As Figure 4 presents, the model lets some buildings deteriorate below the acceptable condition and then maintains them in the middle of the period to achieve the minimum standard at the end of the period. For example, building B, D, and E are not directly maintained in the beginning years although their initial conditions are below the minimum acceptable standard.

In contrast with Scenario 1, less money is needed in Scenario 2 for the beginning years, but requires a lot of money in the last years (year 9th and 10th), as Figure 5 shows. Moreover, in year 1st, 2nd, and 6th there is no any maintenance action conducted. This condition happens due to the requirement of achieving the minimum standard at the end of the period. Then, the total budget spent along 10-year time period is approximately 6.7 billion rupiahs. It is more cost-effective than Scenario 1.

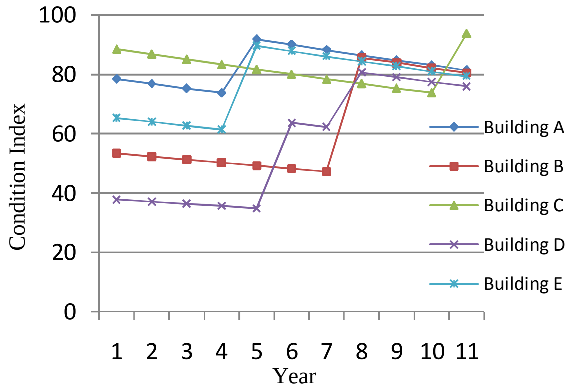

Figure 4. Building Condition Performance of Five Buildings in Scenario 2

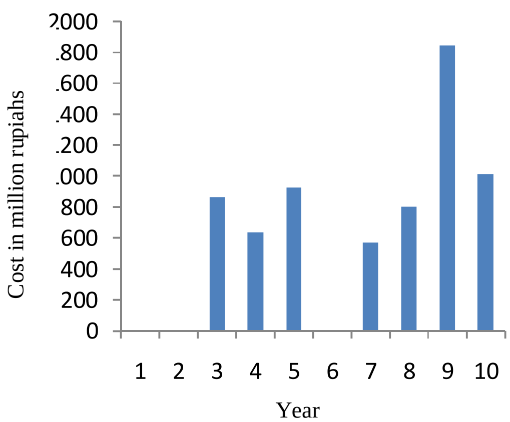

Figure 5. Yearly Budget Spent in Scenario 2

6 Conclusion

This study considers buildings level condition and maintenance budget spent every year. Employing constraint programming, a maintenance optimization model is proposed to solve maintenance strategy selection problems. Two scenarios are conducted to apply the model involving fifteen buildings with different initial conditions in 10-year maintenance plan period.

The result presents the most cost-effective maintenance strategy selection. Scenario 1 shows that most of the buildings must be maintained in the beginning years to achieve the minimum condition standard every year. Meanwhile, Scenario 2 suggests that most of the buildings must be maintained in the last years to reach the minimum condition standard at least at the end of the period, but this scenario does not consider each year buildings condition. For total budget consideration in 10 years period, Scenario 2 spends less money than Scenario 1.

These findings enable owners to predict when a building should be maintained and which maintenance strategy is the most effective. Owners will be able to schedule maintenance actions for all building, so that resources for maintenance strategies can be prepared.

Owners can also forecast budget needed for maintenance treatments each year and they can plan the most effective maintenance budgeting for certain period of time. They can consider which approach is more suitable whether keeping the buildings condition above the acceptable standard but requires more money or targeting the buildings condition to achieve the minimum condition in the last year of period with less money but does not consider the buildings condition for each year.

The results should be treated cautiously. Limited criteria in selecting the maintenance strategies are a major limitation in this study. Future work calls for some criteria to be added to generate better results.

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