Non-Sequential Linear Construction Project Scheduling Model for Minimizing Idle Equipment Using Constraint Programming (CP)

Shu-Shun Liu 1,*, Agung Budiwirawan 2,3 and Muhammad Faizal Ardhiansyah Arifin 2,3

Abstract: Over the last several decades, the scheduling of linear construction projects (LCPs) has been explored extensively by experts. The linear scheduling method (LSM), which focuses on work rate and work continuity, has the advantage of tackling LCPs’ scheduling problems. The traditional LSM uses work continuity to monitor resource allocation continuity on the premise that activities with the same type of work use the same crew. However, some LCPs require a combination of different types of equipment to comprise the crew. Sometimes, parts of different crews require the same types of equipment, and sometimes, the same crew requires different equipment configurations. This causes the pattern of work continuity to be different from the pattern of resource allocation continuity. Therefore, we propose an optimization model of the LSM to minimize idle equipment on a non-sequential linear construction project—i.e., a road network maintenance project. This model is intended to minimize the number of idle equipment and their idle time to achieve more efficient scheduling for linear construction projects. This model offers novel details of resource allocation continuity assessment by taking into account equipment combination and configuration (ECC). Therefore, the scheduling concept used by the proposed model is named the linear scheduling model with ECC (LSM–ECC). The model was developed using constraint programming (CP), as CP has good performance and robustness in the optimization field. The model was implemented to a representation of a road network maintenance project and has satisfactory results.

Keywords: linear project; linear scheduling method; equipment idleness; constraint programming; equipment combination and configuration

1. Introduction

1.1. Background

A construction project consists of a set of activities related to each other to achieve the project’s objectives [1]. Achieving the project’s objectives in the life cycle of the construction project often faces many management problems. One of the prevalent problems is resource availability. Resources are often limited and expensive. Thus, resource management plays an essential factor in project scheduling [2]. Managing resources—equipment, materials, and crews—efficiently in satisfying all project activities becomes an inevitable aspect for construction managers in controlling the project schedule to achieve the project’s goals.

The efficiency of resource management is not only just ensuring resources in satisfying all the activities, but also optimizing the resource usages. Meanwhile, ensuring the project running on schedule with limited resources makes resource management more difficult. Therefore, a detailed and thorough resource scheduling that aligns with the activity schedule is a crucial necessity in construction project scheduling [3,4].
A linear construction project (LCP) is a challenge for a project manager to schedule efficiently. This type of project shares the resources in different spaces either in a sequential or parallel manner. The manager needs to allocate enough resources for maintaining work continuity in various locations of a project, minimizing idle resources, and finishing the project within contract duration \[5,6\]. Sometimes a conflict of resource usage occurs during the execution of LCPs because the movement of activities’ resources is not well planned upon limited shared space \[3,7\]. Consequently, the schedule developed for LCPs not only accounts for precedence constraints of activities but also considers the space and time constraints of the movement of the activity resource \[8\]. The critical path method (CPM) emphasizes scheduling based on precedence relationships between activities \[9\] and is less able to provide monitoring of work continuity for LCPs. On the other hand, the linear scheduling method (LSM) can provide good monitoring of work continuity, so that the LSM is more suitable for scheduling linear construction projects.

One way to achieve the desired scheduling efficiency is to minimize idle resources. Idle resources are defined as resources that have been mobilized but not utilized. Idle resources are unproductive resources, but these idle resources still incur costs, e.g., maintenance costs, rent, and depreciation. By minimizing the amount and time of idle resources, it will minimize unproductive costs which ultimately results in more efficient scheduling.

A road network maintenance project consists of the same type of road maintenance being applied to several road sections. This characteristic includes the road network maintenance project as an LCP. Therefore, an LSM is suitable to be applied as a scheduling method. However, road network maintenance projects have different characteristics compared with regular LCPs to be handled by traditional LSM.

Traditional LSM uses crews as resources used to complete works. The efficiency of linear construction project scheduling is seen from the continuity of work by assuming that the same type of work uses the same crew, while different types of work use different crews. This cannot be applied to road network maintenance projects, which use a combination of heavy equipment as resources to complete their activities. Using the term crew from traditional LSM, the crew used to complete an activity is a set of equipment consisting of several types of equipment as sub-crew and divided into main equipment and supporting equipment. Sometimes, the supporting equipment needed to complete one type of activity is also needed as support equipment to complete another type of activity. Therefore, the profile of work continuity becomes different from the profile of equipment allocation continuity. Based on this condition, we propose a concept of resource allocation dividing the crew into smaller units—sub-crew—which is called equipment combination and configuration (ECC). A more in-depth explanation of ECC is in Section 3.1. Based on the linear scheduling method with ECC concept (LSM–ECC), the authors propose an optimization model for linear construction project scheduling by minimizing idle resources at the sub-crew level, i.e., equipment.

From the point of view of the execution sequence of the repetitive units, traditional LSM requires engineers to define the execution sequence of the repetitive units of an LCP. For sequential/serial linear construction projects, engineers do not have much trouble deciding which repetitive units to begin with. However, the sequence of maintenance work on each road segment of a road network maintenance project is flexible because usually, each road segment has almost the same accessibility. Therefore, engineers have to think about which road segment to work on first to achieve an efficient schedule. To solve this problem, an optimization model that can provide engineers with suggestions for the execution sequence of each road segment to obtain efficient scheduling is needed, even suggestions for non-sequential/parallel execution if possible.

1.2. Objectives

Based on the aforementioned conditions, the authors propose an optimization model to minimize idle equipment for non-sequential linear construction projects. This model
is expected to monitor the continuity of resource allocation at the sub-crew level, i.e., equipment, and minimize the equipment idleness.

This study aims to develop an optimization model of a non-sequential linear construction project to minimize idle equipment using constraint programming (CP). This optimization model is expected to be able to: (1) monitor the mobilization and allocation of equipment; (2) minimize idle equipment in quantity and time; (3) provide the engineer with suggestions on the work sequence of the project’s repetitive unit.

Constraint programming (CP) was used to build this model because CP has several advantages, namely: CP defines a model built using objective functions and a set of constraints without having to define procedures and calculation steps; and logical constraints in CP are easy to define with the help of an optimization programming language (OPL) compared to ordinary mathematical models.

1.3. Paper Structure

The remainder of this paper is structured as follows: Section 2 discusses some previous studies related to scheduling theory, non-sequential linear scheduling, as well as resource allocation and resource-leveling. Section 3 presents the material and method conducted in this study. Section 4 discusses the result of the proposed model applied in three different scenarios. Lastly, Section 5 presents the general conclusion and the opportunity for future research related to this study.

2. Literature Review

There are two main categories of construction projects, namely repetitive and non-repetitive construction projects. A repetitive project consists of multiple repetitive units and requires timely movement of construction resources from one unit to the next unit to repeat the same activities [5]. Repetitive projects can also be classified as typical and non-typical. Activities in a typical repetitive project have the same crew productivity rates that are repeated on different repetitive units. Most of the real construction projects are adjacent to non-typical repetitive projects, which have different repeated productivity rates on different repetitive units [10]. Breaking the continuity of the same activities between repetitive units creates work gaps that cause idle resources and bring additional costs [11]. Hence, maintaining the work continuity in repetitive projects then will ensure constant usage of construction resources and minimizing equipment idle time [10].

Repetitive projects can be divided into linear and non-linear projects according to the linear geometric pattern [12]. In terms of linear projects, this type has repetitive units—a sequence of construction activities [13]. Linear construction projects include characteristics as a series of linear repetitive activities, such as railways, highways, pipelines, and tunnels, while high-rise buildings with typical floors and typical housing projects are considered non-linear repetitive projects [12].

One of the methods that is often used in scheduling is the network-based scheduling method. Critical path method (CPM) and project evaluation and review technique (PERT) are examples of network-based methods [14]. The network-based scheduling method focuses on scheduling based on the precedence relationship between activities. Because this method has a strong definition of the precedence relationship between activities, the schedule of activity—i.e., start time, finish time, etc.—could be calculated easily, and this method is suitable for automatic schedule calculation, such as using computer programs. However, this method does not show the work rate and work continuity of activities. The resource-driven scheduling method focuses on work performance and continuity. Line of balance (LOB) and the linear scheduling method (LSM) are examples of resource-driven scheduling methods.

In construction projects, resources are divided into two main categories, namely renewable resources and non-renewable resources. A renewable resource is a resource that can be repeatedly utilized without replenishment, and a non-renewable resource is a one-time consumable resource and the usage of this resource cannot be repeated [15]. This
study is focused on managing renewable resources, especially construction equipment at a project level. Based on these resource management problems and the crucial resource management role, this study attempts to overcome these challenges from the perspective of the repetitive linear construction project.

The main reason this study utilized LSM is that the network-based scheduling method has great drawbacks in the application of linear construction projects since the network planning methods is difficult in ensuring the work continuity of a linear construction project and leads to a greater risk of idle time of the renewable resource [16]. In the network planning method, more repetitive activities will lead the network growth and make scheduling visualization intricate [17]. Additionally, network schedules are only able to provide a one-dimensional graph in terms of their informational content, which solely shows how sequentially connection activities occur upon a time [18].

LSM depicts the construction schedule of a linear construction project by a rectangular coordinate according to the characteristics of a linear construction project with the horizontal and vertical axes representing the spatial position and schedule of a project, respectively [19]. The two-dimensional coordinate system in LSM broadens the scope of information that can be communicated including the key elements inside the system, for instance, activities, rate of activities, and buffer between activities are employed for illustrating the project schedule then the LSM diagram will be formed [14].

According to the spatial location of the activity, a linear-type activity can be categorized into two types, namely full-span and partial-span linear activity [20]. The major characteristic of a linear type activity in LSM is a rate concept that denotes the spatial progress of the linear activity in unit time, and this concept becomes a differentiation feature compare to the critical path method (CPM) [21]. The slope of a linear-type activity in the LSM diagram indicates the rate of that activity. The slope of linear-type activity can be varied in proportion, depending on the resource usage of the activity. Thus, the accuracy in developing a linear schedule is extremely dependent on the capacity production of the activity resources [22].

The distance between two activities in the horizontal and vertical directions in the LSM diagram is, respectively, named as the distance and time buffer [23]. The buffer in the LSM concept depends on the technical constraints, managerial policy, or other conditions. Furthermore, the minimum/maximum time buffer is defined as the minimum/maximum time between two activities; similarly, the minimum/maximum distance buffer is defined as the minimum/maximum distance between two activities. Commonly the minimum buffer is easy to fulfill; however, in some cases, a maximum buffer needs to interrupt the activity or adjusting its productivity [14].

LSM has a similar concept for controlling activity path (CAP), such as a critical path in a network-based scheduling method. The float activities in the network scheduling method exist in the non-critical path after the critical path is calculated. A similar concept in LSM called the rate float for the float of non-controlling activities or non-controlling segments of activities in the schedule created by LSM appeared while the CAP has been established [2,24]. The number of possible changes in the production rate for a non-controlling linear activity can be specified by the rate float before the non-controlling linear activity becomes a controlling activity. In other words, the rate float is also defined as “the difference between the planned production rate of an activity and the lowest possible production rate without interfering in the buffer” [24]. By shifting non-controlling activities on the available rate float, the LSM model can adjust resource allocation and minimize resource fluctuations to obtain the resource leveling model without changing the original duration schedule [19,25].

Among those aforementioned examples of linear construction projects and challenges of resource management in linear construction projects, this study is focused on scheduling equipment in road network maintenance projects. There are only a few studies that discuss road network maintenance at the project level with detailed renewable resource scheduling. Mizutani et al. [26] proposed an optimal solution for pavement repair that
considers work zone policies at the highway network level. Huang and Lin [27] proposed an arc routing problem approach to solve construction machinery schedules for road maintenance. Aarabi and Batta [28] proposed scheduling for pothole repair using a vehicle routing problem without focusing on machine management scheduling. Research focused on using the linear scheduling method (LSM) for highway construction projects has been performed in prior studies [5,20,29–34]. However, none of those studies have discussed the detail of equipment scheduling, considering equipment idleness in the concept of equipment combination and configuration, as well as mobilization and demobilization of the machinery.

Two leading concepts are associated with how to manage project resources, namely resource allocation and resource leveling [2,35]. The concept of resource allocation is to reschedule the project activity to efficiently manage the limited resources by allowing to exceed project duration planning as minimum as possible [36]. While the concept of resource leveling is to make the resource usage curve during the construction project as flat as possible so it can assist in avoiding short-term peaks and troughs, reduce resource costs and management costs, as well as avert needless losses by keeping the original project duration [36–38]. Accordingly, both of these concepts deal with two dissimilar resource sub-problems that can solely be utilized to a project one after the other rather than simultaneously.

Referring to the basic concept of resource leveling, in smoothing the histogram of resource profile to be as flat as possible, it brings an exact deployment of resources within a project that can minimize renewable resource cost [39]. However, considering the complex mixture of activity relationships in the scheduling, the objective function on resource leveling can be nonlinear and makes the graph that represents the resource profiles become extremely discontinuous. Thus, a small change in resource consumption on activity may create a vast change in the resource profile. According to these advantages of the resource leveling concept and the challenge to solve resource leveling problems, some previous studies have applied various approaches to solving resource leveling problems on the network schedules or linear schedules. Using the definition of buffer and the concept of rate float in the LSM schedule, some previous studies have attempted to resolve the problem of resource leveling in construction projects. Lucko [39] utilized a singularity function in LSM to optimize the resource leveling profile while considering the resource rate changes. Tang et al. [38] present linear scheduling of a railway construction project to level the resource profile for optimum resource usage. Tang et al. [19], proposed a two-stage scheduling system model and algorithm for linear construction project resource leveling to automatically generate a linear schedule including the resource leveling; this study performs according to the example data of highway construction project conducted by Matilla and Abraham [24]. Su and Lucko [17] proposed a combination of LSM and LOB to optimize multiple crew scheduling within and between repetitive activities with singularity functions. By employing new constraints in LSM, namely total resource constraint, resource utilization constraint, and construction mileage constraints, Wang et al. [40] strove to maximize the space–time flexibility of construction activities and optimize the LCP’s resource-leveling. Esfahan et al. [21] considered equipment congestion in road construction proposed a space–time float concept for optimizing the resource scheduling of an LCP. Damci et al. [2], in the framework of LOB, present multi-resource leveling optimization with the principle of optimum crew size and natural rhythm. Ipsilandis [11] adopted the resource leveling concept to minimize project duration or to minimize resource work breaks in linear repetitive projects.

Sometimes a resource allocation problem can be called a resource-constrained project scheduling problem (RCPSP), since the main concept of the resource allocation model is developed to solving resource conflicts by rescheduling activities while minimizing the additional project duration [41]. The main consideration of traditional RCPSP is how to deal with a set of n activities needed to schedule and to minimize a project’s completion time and meet two main constraints: (1) the precedence constraint, and (2) the limited
availability of resources [13]. RCPSP and its variants have been extensively investigated by researchers during the last several decades, since the pioneering work of experts [6–8] about mathematical programming formulations of scheduling problems.

Traditional RCPSP uses given and normally constant resource allocations throughout each activity. Different from the traditional RCPSP, Fündeling and Trautmann [42] proposed a model in which resource requirements and resource allocations must be determined. This resulted in a different “work profile”, which was not limited to a rectangular shape as the traditional RCPSP has been, and “work content”, which was defined as the total amount of resource required to finish an activity. For more general uses, “resource profile” and “resource requirement” are used instead of “work profile” and “work content”, respectively, since resources are not restricted only to human resources.

Recent computer technology has opened many opportunities in solving large-scale and difficult mathematical models efficiently. Taking advantage of this condition, new mathematical models for RCPSP have been formulated and extensively compared by experts [25–27]. Naber and Kolisch [43] proposed four discrete-time model formulations of a resource-constrained project scheduling problem with flexible resource profiles (FRCSP) and compared the model efficiency in terms of solution quality and computational time. These models used decision variables based on previous research [26,28–31] to achieve the shortest project completion time. Leu and Hwang [44] consider using resource sharing in repetitive precast production proposed optimization schedule based on the LOB method. Liu and Wang [45] proposed a resource allocation optimization model in an LCP by employed constraint programming (CP). Zhang et al. [46], in the framework of the line of balance (LOB) method, focus on the learning effect to minimize total resource usage while satisfied all of the demands of work continuity and the target deadline of every activity. Hyari and El-Rayes [5] simultaneously minimize project duration and maximize crew work continuity in bridge construction utilizing the LSM method by considering typical and non-typical repetitive activities. Kong and Dou [47] solve resource-constrained project scheduling problems under multiple time constraints that include a duration constraint of activity, temporal constraint, and resource calendar constraint.

By the nature of resource leveling characteristics, this type of resource management concept is more relevant to linear scheduling. Nevertheless, some previous research has already attempted to combine the resource-leveling concept and resource allocation concept in one single scheduling optimization model. For example, Hegazy employed a genetic algorithm (GA) technique [36], Jun and El-Rayes [41] developed a multi-objective optimization model based on a GA module, Koulinas and Anagnostopoulos utilized bi-objective models [35], Francis Siu et al. applied an integer linear programming technique [48], and Khanzadi et al. [49] utilized a colliding body optimization (CBO) algorithm and charged system search (CSS) technique. Tang et al. [50] solve scheduling optimization problems in transportation-type linear construction projects using a constraint programming (CP) technique.

Total project duration in this study after the optimization process should be the same as with the original duration or can be shorter than the original duration. Thus, this characteristic makes this study adopt the properties of resource-leveling concepts. Moreover, minimizing equipment idleness has a similar concept to make resource usage histogram as flat as possible. However, on the other side, the objective of minimizing equipment resource idleness must also consider the available number of the items of equipment, where this condition has similar properties with resource allocation concepts. Therefore, this study simultaneously utilized both the concept of resource leveling and resource allocation to solve equipment management problems on a road network maintenance project.

This study applied a combination of different types of equipment in one single work crew to serve several activities. Therefore, the resource allocation problem in this study will also adopt the resource sharing concept to maximize the available resource, because, in construction projects, the concept of resource sharing is suitable when meeting the
condition of resource shortage [51]. The concept of resource sharing means to work with greater efficiency or produce extra benefits by using finite resources [52].

Although those previous studies perform a combination concept of resource leveling and resource allocation, none of those previous studies consider the work zone safety during the highway network maintenance by minimizing the lag time between activities and utilizing flexible resource profile in the framework of non-sequential LSM to solve resource idleness problems. Furthermore, none of those studies were able to provide a single group crew (equipment fleet) that combine two different types of equipment, called main equipment and supporting equipment. The supporting equipment will be applied as resource sharing to serve two activities. These will be the key techniques of this study in solving management renewables resource problems on a highway maintenance project.

Table 1 denotes the most relevant research prior to the proposed model.

| Research          | Objective                  | Resource                                      | Activity Duration                                      | Method                                      |
|-------------------|----------------------------|-----------------------------------------------|-------------------------------------------------------|---------------------------------------------|
| [2]               | Resource leveling          | Multiple types of resource.                   | Production rate and duration are based on the resource which requires longest time. | Genetic algorithm (GA)                     |
| [44]              | Multi objective            | Multiple types of resources.                  | Activity duration is based resource allocation.       | Genetic algorithm (GA)                     |
| [38]              | Resource leveling          | The type resource is implicitly represented by the type of work. | Duration is based on resource’s production rate.     | Constraint programming (CP)                |
| [40]              | Resource leveling          | Multiple types of resources used by an activity. | Duration is based on resource’s production rate.     | Quantum-behaved particle swarm optimization (QPSO) |
| [50]              | Resource leveling          | The type resource is implicitly represented by the type of work. | Duration is based on resource’s production rate.     | Constraint programming (CP)                |
| Proposed model    | Resource idleness minimization | Multiple types of resources used by an activity. | Activity duration is based resource allocation and equipment combination and configuration (ECC). | Constraint programming (CP)                |

LSM, work continuity, and resource allocation have been studied extensively by experts in recent decades. However, as far as the author knows, to obtain the efficiency of resource allocation as an objective function, previous studies have always used the concept of resource leveling, which minimizes the deviation of resource allocation from a certain reference line or minimizes daily resource allocation changes. In contrast, the proposed model does not use the traditional resource leveling concept. Alternatively, to achieve resource allocation efficiency, the proposed model minimizes the deviation of resource allocation with mobilized resources, as indicated in Figure 1. In addition, this model also introduces the concept of equipment combination and configuration (ECC), which, to some degree, is almost the same as the concept of shareable resources. The concept of ECC will be discussed in the ECC section.
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3. Materials and Methods

3.1. Model Concept

The optimization model of linear scheduling for minimizing idle equipment was developed based on a road-network maintenance project, hereinafter referred to as the project. A representation of a road-network maintenance project—the object of this study—consists of five repetitive units (road segments). Each road segment consists of asphalt stripping activity, asphalt resurfacing activity, and road marking activity (Figure 2).

![Figure 1. Idle equipment definition.](image1)

3.1.1. Project Characteristics

A road-network maintenance project relies on heavy equipment to finish its activities. For example, an asphalt stripping activity uses an asphalt-milling machine (AM) to grind and strip the existing asphalt layer. Thus, in this optimization model, the schedule of activities is represented as the schedule of the main equipment used by related activity, and vice versa. Table 2 denotes the main equipment used by each activity type in the project.

![Figure 2. Road-network maintenance project.](image2)

| Activity Name       | Main Equipment                  |
|---------------------|---------------------------------|
| Asphalt stripping   | Asphalt milling machine (AM)    |
| Asphalt resurfacing | Asphalt finisher machine (AF)   |
| Road marking        | Road marking machine (ME)       |

3.1.2. Equipment Combination and Configuration (ECC)

Traditional LSM uses the term ‘crew’ to describe the resources used to do work. Therefore, in traditional LSM, the continuity of resource allocation can be represented as a continuity of work, and vice versa. However, at the project site, the crew consists of several types of interdependent resources, hereinafter referred to as sub-crew, so that the
continuity of one type of work is not always the same as the allocation continuity of the related sub-crew.

In the road network maintenance project, a crew needed to finish a work consists of several sub-crews—i.e., equipment. The main equipment requires supporting equipment to work properly. Asphalt stripping activity requires AM as the main item of equipment to peel off the existing road surface. The material resulting from the peeling of the road surface must be disposed of using dump trucks (DT). Because the capacity and duty cycle between AM and DT are different, each unit of AM requires several units of DTs; in this case, for example, one unit of AM requires five units of DTs. Such an arrangement is proposed by this study as equipment combination and configuration (ECC). Table 3 denotes the ECC applied to this project.

Table 3. Equipment combination and configuration (ECC) for each crew.

| Activity Name       | Crew | Main Equipment              | Supporting Equipment       |
|---------------------|------|-----------------------------|----------------------------|
| Asphalt stripping   | 1    | Asphalt milling machine (AM)| 5 Dump trucks (DT)         |
| Asphalt resurfacing | 2    | Asphalt finisher machine (AF)| 4 Dump trucks (DT),        |
|                     |      |                             | 2 pneumatic rollers (PR)   |
| Road marking        | 3    | Road marking machine (ME)   | -                          |

ECC creates a different situation compared to traditional LSM, which uses work continuity to assess scheduling efficiency. Figures 3 and 4 depict the ECC schema and the resource allocation monitoring scheme, respectively.

Dump trucks serve as supporting equipment for Crew 1 for asphalt stripping activity and also as supporting equipment for Crew 2 for asphalt overlaying activity (Figure 3). From a traditional LSM perspective, asphalt stripping activity and asphalt overlaying activity use different resources, namely Crew 1 and Crew 2, so that the continuity of the allocation of Crew 1 and Crew 2 is in line with the continuity of asphalt stripping activity and asphalt overlaying activity, respectively. However, from the ECC perspective, dump trucks are allocated to asphalt stripping activity and asphalt overlaying activity, so that the continuity of dump truck allocation follows the scheduling of these two types of activities (Figure 4).
allocation of Crew 1 and Crew 2 is in line with the continuity of asphalt stripping activity and asphalt overlaying activity, respectively. However, from the ECC perspective, dump trucks are allocated to asphalt stripping activity and asphalt overlaying activity, so that the continuity of dump truck allocation follows the scheduling of these two types of activities (Figure 4).

Figure 4. Equipment allocation continuity schema.

3.1.3. Model Features

This optimization model proposed two features to improve the practicality and efficiency of equipment allocation. Those features are (1) resource dependency between main equipment and supporting equipment, and (2) flexible resource profile.

Resource dependency in this model is defined as the dependency between main equipment and supporting equipment. The traditional linear scheduling method (LSM) applies the term crew as a resource of activities. One type of crew is allocated to a particular type of activity and shared among the same type of activities. The proposed model divides the crew into equipment. In this model, the crew consists of some main equipment and supporting equipment. Therefore, shared resources in the proposed model are not at the crew level but the equipment level instead. This opens possibilities of shared equipment between different types of work. Figure 5 shows crew allocation to activities in a traditional way and the addition of the resource dependency concept. Besides the main equipment used to finish an activity, this model also considers supporting equipment, which is important in maintaining the work performance of the main equipment. Asphalt stripping activity needs an asphalt milling machine (AM) as the main equipment. However, an asphalt milling machine needs dump trucks (DT) to take the product of the asphalt stripping process to the dumping area. The number of dump trucks supporting the asphalt milling machine is important to match both types of equipment’s work rates. Besides the asphalt milling machine, the asphalt finisher machine—the main equipment of asphalt overlaying activity—also needs dump trucks to support its work. This model also tackles the condition where some main items of equipment of several activities need the support of one type of supporting equipment. This condition became a challenge especially when there is a shortage of resource availability.
Each road segment of this project consists of three serial activities, which are (1) asphalt stripping, (2) asphalt resurfacing, and (3) road marking. Asphalt stripping starts the works on every segment. Asphalt milling machines (AM) act as the main equipment for this activity. The asphalt milling machine is supported by dump trucks (DT) to collect and take the product of the asphalt milling machine to the dumping area. In this model, some dump trucks (DT) are assigned to one asphalt milling machine (AM) to match the work rate between the asphalt milling machine and the dump trucks to achieve the most efficient work rate. The unmatched work rate of either the main equipment or the supporting equipment would result in lower overall work performance. Asphalt resurfacing is the succeeding activity of the asphalt stripping activity. Asphalt finishers (AF), pneumatic rollers (PR), and dump trucks (DT) are used in this asphalt resurfacing activity. Asphalt finishers are the main equipment used to resurface the road segment supported by several pneumatic rollers and dump trucks. Pneumatic rollers compact the new pavement surface, and dump trucks supply hot-mixed asphalt from an asphalt mixing plant to the asphalt finisher. Several pneumatic rollers and dump trucks are assigned to one asphalt finisher to match the work rate among the equipment to achieve the most efficient work performance. Road marking is the last activity to execute on each road segment. Road marking is the succeeding activity of asphalt resurfacing activity. Road marking machines (ME) are assigned to this road marking work as the main equipment. Figure 3 shows the schema of main and supporting equipment allocation for this model.

Flexible resource profiles are the second feature of the proposed model as an addition to the linear scheduling method. In the traditional linear scheduling method, the resource allocation profile commonly has a constant rate; thus, it makes the shape of a bar. As mentioned above, for road safety reasons, this model omits time floating buffer, which causes a disadvantage in minimizing idle equipment. To deal with this problem, this model implements flexible shapes of resource allocation profiles to provide a different allocation of equipment during the transition between the same type of activities on different road segments. However, it is not an easy task to move equipment between activities or between repetitive units. Thus, this model limits the shape of the resource profile only as a bar or trapezoid shape.

3.1.4. Model Objective

The objective of this model is to minimize equipment idleness caused by valleys of equipment allocation profile (Figure 1). Idle equipment is not calculated by the difference between maximum available equipment and allocated equipment at a time, but the dif-
ference between mobilized equipment and allocated equipment at a time. The proposed model achieves the objective by eliminating these valleys.

3.2. Model Formulation

The optimization model for minimizing idle equipment of road network maintenance project was developed following the model development workflow (Figure 6) and using constraint programming engine of IBM ILOG CPLEX Optimization Studio version 12.10 and OPL modeling language.

![Figure 6. Optimization model development workflow.](image)

This model binds activities to the allocation of their main equipment. Therefore, the proposed scheduling model schedules activities as the main equipment scheduling. The precedence relationships between activities are implemented as precedence relationships between main items of equipment.

This model consists of five parts, which are: (1) input data; (2) decision variable; (3) decision expression; (4) objective function; and (5) constraints.

3.2.1. Input Data

Input data are parameters set before the optimization process started. These data are not changed during the optimization process. Input data are expressed by input variables and structured using indices. Tables 4 and 5 denote indices and input variables used by the proposed model, respectively.

| Index | Description                  | Range            |
|-------|------------------------------|------------------|
| $i, m$| Index of equipment type      | 1 ... number of equipment types |
| $j$   | Index of a road segment      | 1 ... number of road segments |
| $k$   | Index of time (day)          | 1 ... contract period |
Table 5. Input variables used by the proposed model.

| Variable | Description |
|----------|-------------|
| $u$      | Number of equipment types |
| $r$      | Number of road segments |
| $d$      | Contract period |
| $pr_{ij}$ | Precedence relationship between main items of equipment. This variable holds the precedence relationship data between predecessor $m$ and successor $i$ in road segment $j$. It contains values of zero and one. For example, $pr_{123} = 1$ means on the road segment 3, main equipment 1 is the predecessor of main equipment 2. The number of main items of equipment required to finish an activity. This variable holds the number of main items of equipment $i$ required on the road segment $j$. $PE_{r12} = 4$ means 4 unit-day of main equipment type 1 is required to finish the related activity on road segment 2. If one unit of main equipment type 1 is allocated, the activity will be finished in four days, or if two units of main equipment 1 are allocated, the activity is finished in two days, etc. The ratio between supporting equipment and main equipment. This variable describes the relationship between supporting equipment $i$ and main equipment $m$ on the road segment $j$. $R_{241} = 5$ means that, on the road segment 2, equipment 4 is the supporting equipment of equipment 1, with a ratio of 5:1. |
| $PE_{rij}$ | The number of main items of equipment required to finish an activity. |
| $R_{jim}$ | The ratio between supporting equipment and main equipment. |
| $Av_{i}$ | The number of available items of equipment. |

3.2.2. Decision Variables

Decision variables are the objects of the optimization process. The optimization algorithm searches the optimized values of the decision variables to achieve the objective function. The values of these variables are changed during the optimization process until they reach the considered optimum values based on the objective function. $PE_{ijk}$ is used as the decision variables of this model. $PE_{ijk}$ is the number of allocated main items of equipment, $i$, on the road segment $j$ on day $k$. $PE_{123} = 2$ means 2 units of main equipment type 1 are allocated on road segment 2 on day 3.

3.2.3. Decision Expressions

CPLEX constraint programming and OPL programming language allow the user to use decision expressions. Decision expressions are mathematical expressions for variables that are not the target of the optimization algorithm. For example, a mathematical expression $b = a + 2$, $a$ is the decision variable; therefore, the value of $a$ is based on the optimization algorithm. However, $b$ is not the target of the optimization algorithm. The value of $b$ only follows the value of $a$; thus, to define the value of $b$, a decision expression is used.

$E_{ijk}$ is the allocation of equipment $i$ of road segment $j$ on day $k$. Equipment allocation is the total allocation of the equipment as main equipment and supporting equipment; thus, it is the sum of the allocation number as main equipment and the allocation number of supported main equipment multiplied by the ratio of supporting equipment to main equipment (Equation (1)).

$$E_{ijk} = ME_{ijk} + \sum_{m} SMratio_{jim} \times ME_{mjk} \quad (1)$$

$Ereq_{ij}$ is the required allocation of equipment $i$ on the road segment $j$. The required equipment allocation is the sum of the allocation as main equipment and as supporting equipment. This variable acts as a control variable whether the allocation of particular equipment has reached the required allocation or not (Equation (2)).

$$Ereq_{ij} = MEreq_{ij} + \sum_{m} SMratio_{jim} \times MEreq_{mj} \quad (2)$$
Equation (3) defines variable \( Ed_{ik} \) as the total allocation of equipment \( i \) on day \( k \) of all road segments. This variable is used in a constraint to limit the equipment allocation to the available equipment on one day.

\[
Ed_{ik} = \sum_j E_{ijk}
\]  

(3)

\( Er_{ij} \) is the total allocation of equipment \( i \) of road segment \( j \). This expression (Equation (4)) defines this variable, which is used to track the total allocation of particular items of equipment on a road segment. Combined with variable \( Ereq_{ij} \), this variable is used to check if the allocation of a particular item of equipment has met the requirement.

\[
Er_{ij} = \sum_k E_{ijk}
\]  

(4)

Equation (5) defines variable \( E_{tot}^{ijk} \), which tracks the total allocation of equipment \( i \) of road segment \( j \) from day 1 to day \( k \). This variable is used to track whether an activity has finished or not.

\[
ME_{tot}^{ijk} = \sum_{n=1}^k ME_{ijn}
\]  

(5)

Variable \( F_{ijk} \), defined by Equation (6), identifies whether equipment \( i \) of road segment \( j \) has finished on day \( k \). It has the value of zero and one. The value of zero means the equipment \( i \) of road segment \( j \) has not been completely allocated on day \( k \). The value of one means it has been allocated completely.

\[
F_{ijk} = \begin{cases} 
1 & \iff ME_{tot}^{ijk-1} = ME_{req}^{ij} \\
0 & \iff ME_{tot}^{ijk-1} \neq ME_{req}^{ij}
\end{cases}
\]  

(6)

Equation (7) defines variable \( precPass_{jimk} \), which is the indicator if equipment \( m \) as the predecessor of equipment \( i \) of road segment \( j \) has finished on day \( k \). If \( precPass_{jimk} \) has the value of zero, it means equipment \( m \) of road segment \( j \) is not considered finished. Equipment \( m \) is considered finished if equipment \( m \) is not the predecessor of equipment \( i \), or equipment \( m \) has been allocated as required.

\[
precPass_{jimk} = \begin{cases} 
1 & \iff \left( prec_{jim} = 0 \right) \lor \left( prec_{jim} = 1 \land F_{mjk} = 1 \right) \\
0 & \iff \overline{\left( prec_{jim} = 0 \right)} \lor \left( prec_{jim} = 1 \land F_{mjk} = 1 \right)
\end{cases}
\]  

(7)

Equations (8) and (9) define variables \( Eb_{max}^{ik} \) and \( E_{max}^{ik} \), which are the maximum daily allocation of equipment \( i \) from day 1 to day \( k \) and the maximum daily allocation of equipment \( i \) from day \( k \) to the last day, respectively. These variables are used as the benchmark for idle equipment calculation.

\[
Eb_{max}^{ik} = \max_{m \in 1..k} Ed_{im}
\]  

(8)

\[
E_{max}^{ik} = \max_{m \in k..d} Ed_{im}
\]  

(9)

Variables \( eb_{ik} \) and \( ea_{ik} \), defined by Equations (10) and (11), are the number of idle items of equipment based on maximum daily allocation benchmark before day \( k \) and after day \( k \), respectively. The value of these variables would be assessed by Equation (12) to determine the value of idle equipment. Variable \( e_{ik} \), defined by Equation (12), is the number of idle items of equipment on day \( k \).

\[
eb_{ik} = \begin{cases} 
Eb_{max}^{i,k-1} - Ed_{ik} & \iff Ed_{ik} < Eb_{max}^{i,k-1} \\
0 & \iff Ed_{ik} \geq Eb_{max}^{i,k-1}
\end{cases}
\]  

(10)

\[
ea_{ik} = \begin{cases} 
E_{max}^{i,k+1} - Ed_{ik} & \iff Ed_{ik} < E_{max}^{i,k+1} \\
0 & \iff Ed_{ik} \geq E_{max}^{i,k+1}
\end{cases}
\]  

(11)
\[
e_{ik} = \begin{cases} 
    eb_{ik} & \iff eb_{ik} \leq ea_{ik} \land (eb_{ik} > 0 \land ea_{ik} > 0) \\
    0 & \iff (eb_{ik} > 0 \land ea_{ik} > 0)
\end{cases}
\] (12)

Variables \( ET_{ik} \) and \( T_k \), defined by Equations (13) and (14), are variables for identifying whether equipment \( i \) and any equipment is allocated on day \( k \). Variable \( T_k \) is also used to count the duration of the project.

\[
ET_{ik} = \begin{cases} 
    1 & \iff Ed_{ik} > 0 \\
    0 & \iff Ed_{ik} \leq 0
\end{cases}
\] (13)

\[
T_k = \begin{cases} 
    1 & \iff \sum_i ET_{ik} > 0 \\
    0 & \iff \sum_i ET_{ik} \leq 0
\end{cases}
\] (14)

3.2.4. Objective Function

The objective of this optimization model is to minimize idle equipment of a road-network maintenance project. Variable \( e_{ik} \), which is defined by Equation (12), is used to define the objective function of this model. The objective function (Equation (15)) is the sum of variable \( e_{ik} \) for all items of equipment \( i \) and day \( k \).

\[
\sum_x \sum_k e_{ik}
\] (15)

3.2.5. Constraints

Equations (16)–(24) are constraints regulating the precedence relationship between main items of equipment. These equations are expressed using the syntax OPL programming language used by IBM ILOG CPLEX CP engine. These constraints are defined using conditional assessment; thus, OPL implication syntax is used for these definitions.

Equations (16)–(19) regulate the precedence relationship for main equipment, which do not have other items of equipment as their predecessors. These constraints are started by a conditional assessment of whether a particular item of equipment has other items of equipment as its predecessor, shown by the expression of \( \sum_m prec_{im} = 0 \). If the assessment results in a true value, it means equipment \( i \) does not have any predecessors. Equation (16) defines that, if equipment \( i \) of road segment \( j \) does not have any predecessors, then equipment \( i \) could be allocated on day \( k \).

\[
\sum_m prec_{im} = 0 \Rightarrow E_{ijk} \geq 0
\] (16)

Constraints defined by Equations (17) and (18) state that if equipment \( i \) of road segment \( j \) does not have any predecessors allocated on the previous days, and it has not reached the number required allocation, it needs to be allocated on day \( k \).

\[
\sum_m prec_{im} = 0 \land E_{ij,k-1} > 0 \land Etot_{ij,k-1} < Ereq_{ij} \Rightarrow E_{ijk} \geq 0
\] (17)

\[
\sum_m prec_{im} = 0 \land E_{ij,k-1} > 0 \land Etot_{ij,k-1} < Ereq_{ij} \Rightarrow E_{ijk} \leq Ereq_{ij} - Etot_{ij,k-1}
\] (18)

Equation (19) defines that, if equipment \( i \) of road segment \( j \) has reached the number of required allocations, it is not allowed to be allocated anymore.

\[
\sum_m prec_{im} = 0 \land Etot_{ij,k-1} = Ereq_{ij} \Rightarrow E_{ijk} = 0
\] (19)

Equations (20)–(24) regulate the precedence relationship for the main items of equipment, which have other items of equipment as their predecessors. These constraints are...
started by a conditional assessment of whether particular items of equipment have other items of equipment as their predecessors, shown by the expression of $\sum_{m} prec_{jim} > 0$. If the assessment results in a true value, it means the items of equipment $i$ have some predecessors. Equation (20) defines that, if equipment $i$ of road segment $j$ does not have any predecessors, then equipment $i$ could be allocated on day $k$.

Equation (20) defines that, if the items of equipment $i$ of road segment $j$ have predecessors, they are not allowed to be allocated on day 1.

$$\sum_{m} prec_{jim} > 0 \Rightarrow E_{ij1} = 0$$ (20)

If item of equipment $i$ of road segment $j$ on day $k$ has not had all its predecessors considered finished, it is not allowed to be allocated. This condition is defined by Equation (21). The expression $\sum_{m} precPass_{jimk} < u$ shows that the number of items of equipment considered finished on day $k$ is smaller than the registered equipment; thus, it means some of the predecessors are still not finished.

$$\sum_{m} prec_{jim} > 0 \land \sum_{m} precPass_{jimk} < u \Rightarrow E_{ijk} = 0$$ (21)

The expression $\sum_{m} precPass_{jimk} = u$ of Equations (22) and (23) shows that all registered equipment is considered finished on day $k$; thus, it means all predecessors of equipment $i$ have been finished. This condition allows for equipment $i$ to be allocated on day $k$.

$$\sum_{m} prec_{jim} > 0 \land \sum_{m} precPass_{jimk} = u \land Etot_{ij,k-1} < Ereq_{ij} \Rightarrow E_{ijk} > 0$$ (22)

$$\sum_{m} prec_{jim} > 0 \land \sum_{m} precPass_{jimk} = u \land Etot_{ij,k-1} < Ereq_{ij} \Rightarrow E_{ijk} \leq Ereq_{ij} - Etot_{ij,k-1}$$ (23)

Equation (24) defines that, if item of equipment $i$ of road segment $j$ on day $k-1$ has been allocated as required, equipment $i$ is not allowed to be allocated anymore.

$$\sum_{m} prec_{jim} > 0 \land \sum_{m} precPass_{jimk} = u \land Etot_{ij,k-1} = Ereq_{ij} \Rightarrow E_{ijk} = 0$$ (24)

Constraints expressed by Equations (25) and (26) limit the maximum daily allocation of each item of equipment to the number of available items of equipment and reach the required allocation on each road segment, respectively.

$$Ed_{ik} \leq Eavail_{i}$$ (25)

$$Er_{ij} = Ereq_{ij}$$ (26)

The constraint defined by Equation (27) makes sure that the project is started on day 1.

$$T_{1} = 1$$ (27)

3.2.6. Model Implementation Scenario

The road-network maintenance project scheduling—termed as the scheduling problem for the rest of this paper—was solved by three scenarios. The first scenario solves the scheduling problem by traditional LSM. This scenario acts as a benchmark for comparison to other scenarios. The second scenario solves the scheduling problem using the proposed model with the limitation of rectangular resource profiles. The third scenario solves the scheduling problem using the proposed model utilizing flexible resource profiles. Table 6 shows the comparison of the scenarios.
Table 6. Comparison of scenarios.

| No. | Aspect          | Scenario 1                      | Scenario 2                      | Scenario 3                      |
|-----|----------------|--------------------------------|--------------------------------|--------------------------------|
| 1   | Solving method | Traditional LSM                | Proposed model                  | Proposed model                  |
| 2   | Execution order| predetermined                 | Not predetermined              | Not predetermined              |
| 3   | Execution order sequence | Serial                       | Parallel                       | Parallel                       |
| 4   | Resource profile | Rectangular                  | Rectangular                    | Trapezoidal                   |
| 5   | Resource       | Crew                           | Main and supporting equipment   | Main and supporting equipment |

The scheduling problem solved has similar data for each scenario, except precedence relationship between road segments and type of resource used by activities. Tables 5 and 6 show resource requirements and resource availability for the project scheduling problem, respectively. The precedence relationship of Scenario 1 is different from that of the other two scenarios. Since it has a predetermined execution sequence, Scenario 1 has an additional precedence relationship of asphalt milling machine allocation between road segments. It is set that road segment 1 is executed the first time and road segment 5 is executed the last. Figure 7 shows the precedence relationship used by Scenario 1. Scenario 1 also has a different type of resource. It does not have equipment dependency; thus, it uses the more traditional sharing, that is, ‘crew’ level resource sharing. In this scenario, the crew is the main equipment of the particular activity without dependency on supporting equipment—as shown in Figure 8. Scenarios 2 and 3 use precedence relationship and equipment allocation schema, as shown Figures 1 and 3, respectively.

![Figure 7. Precedence relationship of scenario 1.](image)

![Figure 8. Equipment allocation schema for Scenario 1.](image)

### 4. Result and Discussion

Road network maintenance project scheduling problem was solved in three scenarios. Scenario 1 used the traditional linear scheduling method (LSM) to solve the scheduling problem. Repetitive units—road segment works—were executed sequentially using a predetermined sequence. Scheduling began with the execution of road segment 1 and
ended with road segment 5. When an activity is completed on a road segment, the crew will carry out the same type of activity on the next road segment without having to wait for the entire sequence of activities on the previous road segment to complete. Rectangular or uniform resource profiles were applied in this scenario. This scenario served as a comparison reference for the other two scenarios, i.e., Scenario 2 and Scenario 3.

Scenario 2 and Scenario 3 applied the proposed model for minimizing idle equipment. Road segments’ execution does not have to be sequential. In addition to sequential execution, road segments could be carried out in parallel as long as the required equipment is still available. If road segments are carried out sequentially, the order in which the work is undertaken is not predetermined. This optimization model would determine the sequence of road segments’ execution to achieve the model’s objectives. Scenario 2 and Scenario 3 utilized rectangular and flexible resource profiles to solve the scheduling model, respectively. These scenarios—Scenario 2 and Scenario 3—were compared to Scenario 1 to show the advantages offered by the proposed model. The result of Scenario 2 would also be further compared to the result of Scenario 3 to show the difference caused by flexible resource profiles.

The model was run on the Intel Xeon Silver 4112 platform with 16 GB of RAM. The time needed to complete one scenario was about 20 min.

4.1. Scenario 1: Traditional LSM

The traditional linear scheduling method (LSM) was used to solve the scheduling problem as Scenario 1. Tables 7 and 8 show resource requirements and resource availability of this scenario, respectively. The road segment execution had a predetermined sequence, starting from road segment 1 and ending by road segment 5—as shown by Figure 7, and followed by a serial execution order. Resource allocation for this scenario was limited to a rectangular resource profile and did not implement the relationship between main equipment and supporting equipment. The resource allocation schema used by this scenario is shown in Figure 8. While most of the characteristics of this scenario follow traditional LSM, this scenario limits the schedule not to have a lag time between activities in one road segment, and once an activity is started, it has to be continuously executed until the activity is finished.

Table 7. Resource requirements.

| Road No. | Pavement Stripping: AM (Unit-Day) | Pavement Overlaying: AF (Unit-Day) | Road Marking: ME (Unit-Day) |
|----------|---------------------------------|---------------------------------|--------------------------|
| 1        | 2                               | 5                               | 2                        |
| 2        | 5                               | 13                              | 26                       |
| 3        | 3                               | 7                               | 14                       |
| 4        | 2                               | 6                               | 12                       |
| 5        | 3                               | 7                               | 14                       |

Table 8. Available resource.

| No. | Equipment Type               | Amount |
|-----|------------------------------|--------|
| 1   | Asphalt stripping equipment (AM) | 3 unit |
| 2   | Asphalt finishing equipment (AF) | 3 unit |
| 3   | Marking equipment (ME)         | 1 unit |
| 4   | Dump truck (DT)                | 14 unit|
| 5   | Pneumatic roller (PR)          | 6 unit |

The road segment execution follows a serial sequence. When asphalt stripping activity in one segment finished, it was followed by its succeeding activity—asphalt spreading.
activity. At the same time, asphalt stripping activity on the next road segment was allowed to start. Asphalt stripping activity of the next road segment could start when it met other constraints, such as to ensure that it could be followed by its succeeding activities without lag time. Schedule and equipment allocation is shown in Figure 9.

Figure 9. Schedule and equipment allocation of Scenario 1.

The schedule resulted in Scenario 1 having a project execution duration of 28 days and 87 units of idle equipment. Idle equipment resulted from this scenario is caused by the lack of resource availability and time buffer. The number of resources available in this scenario did not have enough amount to apply different work rates to the activities. Combined with the lack of time buffer, this scenario could not shorten or lengthen each activity’s duration and it could not offset the activity’s execution timing.
4.2. Scenario 2: Proposed Model with the Rectangular Resource Profile

Scenario 2 used the proposed model to solve the scheduling problem with a limitation of rectangular resource profile. This scenario has the same resource requirement and resource availability as Scenario 1—shown in Tables 7 and 8.

This scenario opens the possibilities of executing repetitive units by serial or parallel sequence. All supporting equipment availability are set to a high enough amount that these supporting items of equipment can support the main items of equipment that need them, even in parallel execution.

The result of the linear schedule of this scenario is shown in Figure 10. Asphalt stripping and asphalt spreading activities were executed in parallel at some span of duration, while road marking activities were executed in serial sequence. Figure 10 also shows the equipment allocation schedule. Some idle equipment happened at the total allocation of asphalt milling machine, road marking machine, and dump truck.

Figure 10. Schedule and equipment allocation of Scenario 2.
The optimization model results project execution duration of 29 days and nine units of idle equipment. The ability to execute activities in parallel applied in this scenario allowed the model to flatten the resource allocation profile and reduced a significant amount of idle equipment compared to the traditional LSM. However, this model is limited to a rectangular resource profile; thus, it could not apply a gradual increase in resource allocation at the beginning and a gradual decrease in resource allocation at the end of an activity’s execution.

4.3. Scenario 3: Proposed Model with the Flexible Resource Profile

The proposed model with a flexible resource profile was applied to the scheduling problem as Scenario 3. This scenario opens the alternatives of executing repetitive units by serial or parallel sequence and allocating main equipment using flexible resource profiles to minimize idle equipment. Tables 7 and 8 show resource requirements and resource availability of this scenario, respectively. All supporting equipment availability is set to a high enough amount that these supporting items of equipment can support the main items of equipment that need them, even in parallel execution.

Figure 11 shows the schedule and equipment allocation of Scenario 3. Asphalt stripping and asphalt spreading activities were executed in parallel at some span of duration, while road marking activities were executed in serial sequence. Since this scenario allowed the implementation of flexible resource profiles, the main equipment allocations of each road segment were shaped into trapezoids. Thus, the model could apply a gradual increase and gradual decrease in resource allocation at the beginning and the end of the activity’s execution duration.

The optimization model results project execution duration of 25 days and nine units of idle equipment. The ability to execute repetitive units—road segments—in fully or partially parallel execution and the implementation of flexible resource profile could decrease a significant amount of idle equipment compared to the traditional LSM and result in a shorter duration compared to the second scenario.

4.4. Comparison

This model was intended to minimize idle equipment in a non-sequential linear construction project, i.e., a road-network maintenance project. This model proposed several improvements compared to previous models, which are: (1) non-predetermined road segment execution sequence; (2) serial and parallel execution alternatives; (3) dependency between main equipment and supporting equipment; and (4) application of flexible resource profile. Thus, this model was implemented into three scenarios to prove that the model could handle the proposed improvements. The first scenario uses traditional LSM to solve the scheduling problem and acts as the basis for comparison to the other scenarios. The second scenario applies the proposed model with the limitation of rectangular resource profiles and has abundant supporting equipment availability. The third scenario implements the proposed model with flexible resource profiles. The second and third scenario was intended to show the advantage of the proposed model compared to the traditional LSM. Table 9 shows the comparison of the optimization results among implemented scenarios.
The model could handle the proposed improvements. The first scenario uses traditional LSM to solve the scheduling problem and acts as the basis for comparison to the other scenarios. The second scenario applies the proposed model with the limitation of rectangular resource profiles and has abundant supporting equipment availability. The third scenario implements the proposed model with flexible resource profiles. The second and third scenario was intended to show the advantage of the proposed model compared to the traditional LSM. Table 9 shows the comparison of the optimization results among implemented scenarios.

![Figure 11. Schedule and equipment allocation of Scenario 3.](image)

Table 9. Comparison of the optimization results.

| No. | Aspect          | Scenario 1          | Scenario 2          | Scenario 3          |
|-----|----------------|---------------------|---------------------|---------------------|
| 1   | Idle equipment | 87 unit-day         | 9 unit-day          | 9 unit-day          |
| 2   | Duration       | 28 days             | 29 days             | 25 days             |
| 3   | Execution order| predetermined       | Not predetermined   | Not predetermined   |
| 4   | Execution sequence | Serial               | Parallel             | Parallel             |
| 5   | Resource profile | Rectangle           | Rectangle           | Trapezoid           |
| 6   | AM utilization | 2                   | 2                   | 2                   |
| 7   | AF utilization | 2                   | 3                   | 3                   |
| 8   | ME utilization | 2                   | 1                   | 2                   |
The proposed model proved to be able to implement the proposed improvement mentioned above. Scenario 1, implementing traditional LSM, assigned repetitive units—road segments—by serial predetermined execution order. The equipment allocation schedule (Figure 9) shows some idle equipment happened because there is not any possibility to float a particular activity to meet work continuity.

The result of Scenario 2 and Scenario 3 shows that the proposed model was able to implement parallel execution for the project’s repetitive units as long as it met the constraint of resource availability. In addition to the ability of parallel execution, Scenario 3 also shows the advantage of flexible resource profile to rectangular resource profile. The flexible resource profile allowed the implementation of a gradual increase and gradual decrease in resource profile at the beginning and the end of an activity execution duration, respectively. Scenario 2 and Scenario 3 have nine unit-days of idle equipment compared to 87 unit-days of idle equipment in Scenario 1. In addition to the minimization of idle equipment, Scenario 3 also has 25 days of project duration, which is shorter than in other scenarios.

5. Conclusions

The proposed model has succeeded in achieving its objectives from several points of view, namely project characteristics, model features, and model objectives. From the point of view of project characteristics, this model successfully accommodates the characteristics of a road network maintenance project, which are: (1) non-predetermined sequence of repetitive unit’s execution, (2) serial or parallel execution of repetitive units, (3) zero lag time between activities inside a repetitive unit, and (4) non-preemptive execution of each activity (shown by the Gantt charts of Figures 10 and 11).

The proposed model succeeded to implement the features offered by this model. Resource dependency between main equipment and supporting equipment opens a new sight of resource allocation continuity. The crew consists of main equipment and supporting equipment and the number of equipment assigned to the crew. Compared to traditional LSM, which considers resource sharing at the crew level, this model shares resources at the equipment level. Thus, resource allocation continuity is observed by the allocation of a particular type of equipment, whether that particular equipment is assigned to the same type or a different type of crew.

The next feature of the proposed model is the implementation of flexible resource profiles. This model proved to obtain shorter project duration by the implementation of flexible resource profiles compared to the more traditional resource profiles—rectangular resource profiles.

From an optimization objective point of view, the proposed model has succeeded to minimize idle equipment of a non-sequential linear construction project by using constraint programming. This model calculated idle equipment based on the difference between actual mobilized equipment and the actual allocated equipment at a particular time. This calculation is more realistic than the usage of maximum mobilized equipment or possible available equipment as the reference value of the idle equipment calculation.

From several points of view mentioned above, it could be concluded that compared to the traditional linear scheduling method, this model has achieved several advantages, which are: (1) this model could schedule linear construction project without predetermined execution order; (2) this model could execute repetitive units in a serial or parallel way; (3) this model included a dependency between main equipment and supporting equipment, compared to traditional LSM which consider this resource as crew; (4) this model

| No. | Aspect          | Scenario 1 | Scenario 2 | Scenario 3 |
|-----|----------------|------------|------------|------------|
| 9   | DT utilization | 14         | 14         | 24         |
| 10  | PR utilization | 4          | 6          | 6          |
presented the alternative of using flexible resource profile; and (5) this model could minimize idle equipment, and thus this model could deliver equipment allocation continuity.

This model has several branches as future works. From the concept of resource allocation, this model applied the concept of dependency between main equipment and supporting equipment, which are renewable resources. This concept of dependency between renewable resources could be further explored to the concept of dependency between unrenewable resources and the procurement schedule of renewable and unrenewable resources.

This research is applied to a case of a road network maintenance project. To further ensure that this resource allocation optimization model can be applied to general cases of road network maintenance projects, it is necessary to apply this model to other similar projects as further research.

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