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## Simultaneous multi-criteria optimization for scheduling linear infrastructure projects

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### ABSTRACT

This paper presents a simultaneous multi-criteria optimization approach for scheduling linear infrastructure projects. The proposed model provides planners with sets of non-dominated alternatives and their corresponding tradeoffs. The associated research methodology includes: (1) developing a resource driven scheduling module; (2) applying a multi-criteria optimization technique to optimize the multi-objective scheduling problem; (3) integrating the proposed model with a commercial project management software; and (4) applying the developed model on two literature-drawn case studies. The developed multi-criteria optimization approach utilizes Genetic Algorithms and Pareto Front sorting. The resulting sets of schedules are based on the multiple inter-conflicting objectives of simultaneously minimizing project duration, minimizing cost, minimizing interruptions, and minimizing unit delivery delays. The results indicate that the proposed approach can explore a greater range of solutions compared to existing models. The developed multi-criteria optimization approach can aid planners with proposing optimal set of schedules.

### KEYWORDS

Construction; schedules; repetitive; decision analysis; multi-criteria optimization

## Introduction

Projects with repetitive activities are those where a set of tasks are repeated throughout the project. Repetition can be due to geometric and location layouts or due to multiplications of units. Repetitive activities projects can be classified into two main categories: linear projects such as pipelines, highway and railways; or nonlinear such as multiple housing and high-rise buildings (Moselhi and Hassanein 2003). Linear projects are characterized by continuous transportation of crews among its non-adjacent units. Project managers often opt for assigning construction crews to sections within the project to minimize the transportation across the units. However, upon finishing a section of adjacent units, the construction crew will need to be transported to a different section of the project, as shown in Figure 1. Such continuous transportation of construction crews across non-adjacent units or sections creates significant dynamics throughout the project (Moselhi and Hassanein 2003). Thus, this research focuses on optimizing the schedules of linear infrastructure projects with repetitive activities (LIPRA).

Researchers have developed several specialized scheduling optimization approaches for LIPRA that aimed at optimizing various objective functions such as minimizing project cost, minimizing total duration, minimizing interruptions and resource allocation discontinuities, and minimizing units' delivery delays (Hyari and El-Rayes 2006; Sencouci and Al-Derham 2008; Lucko 2010; Moon et al. 2015; Ioannou and Yang 2016). Despite their undeniable benefits, these approaches still lack the ability of performing pure simultaneous optimization for such multi-criteria problem. The utilization of single objective function limited the aforementioned researches to comprehensively compare the different tradeoffs, and hence the identification of alternative solutions. This is problematic in case the resulting near-optimal schedules cannot be performed in reality due to site conditions.

Through reviewing the advancements made in the last decade in the optimization of LIPRA scheduling, it is clear that in order to achieve a successful LIPRA, the scheduling optimization model must be able to simultaneously: (1) minimize the total project

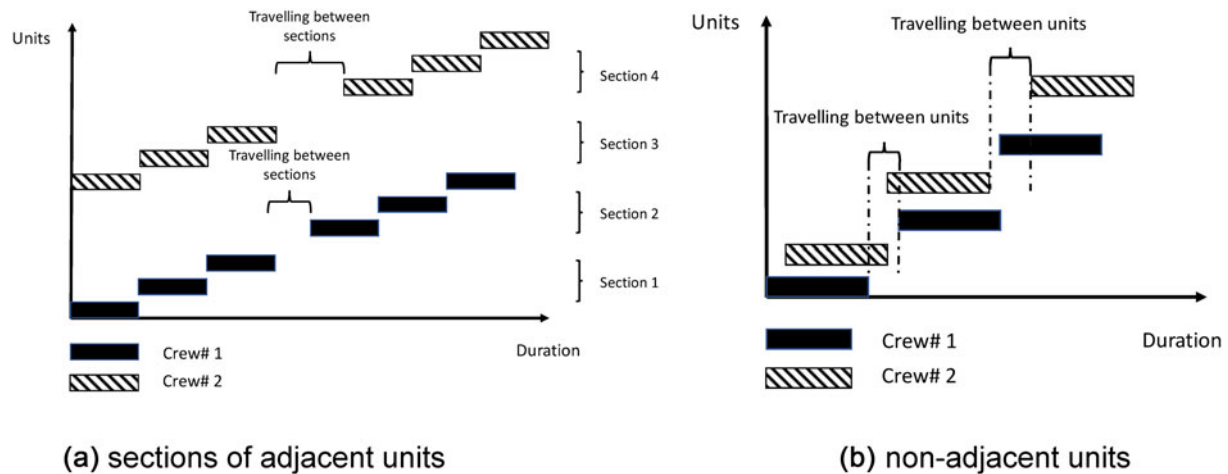


Figure 1. Transportation of crews in LIPRA.

duration while meeting the delivery dates of the different units; (2) minimize the total project cost; (3) maximize the construction work continuity; (4) account for the variability among the crews' production rates; (5) assign multiple crews at the same activity across the different units; and (6) calculate and consider the resources transportation time and cost (Moselhi and Hassanein 2003; Elbelatgi and ElKassas 2008; Sencouci and Al-Derham 2008; Lucko 2011; Ioannou and Yang 2016). The outcome of such simultaneous optimization would be a set of non-dominated optimal schedules that meet the demands of the practitioners and the current evolving project.

### Goal and objectives

The goal of this paper is to present a multi-objective optimization approach for scheduling LIPRA throughout the utilization of new heuristic procedures. The proposed approach is developed to: (1) enable for multi-criteria simultaneous optimization for scheduling linear infrastructure projects and (2) provide planners with sets of non-dominated alternatives and their corresponding tradeoffs based on the multiple inter-conflicting objectives of minimizing project duration, minimizing cost, minimizing interruptions and minimizing unit delivery delays without compromising one over another. Ultimately, the proposed model will aid planners to determine optimal schedule based on the needs and properties of the project.

### Background

Construction projects require planners and project managers to find the schedule that meets project

objectives with optimum utilization of available resources. According to Ioannou and Yang (2016), traditional network techniques, such as critical path method (CPM), have major drawbacks in scheduling LIPRA if no proper optimization module is utilized to account for the linear infrastructure projects unique properties. Traditional network techniques, being a duration oriented approach, are unable to account for: (1) utilization of assigned resources; (2) maintaining work continuity from one unit to another; (3) meeting projects' deadline through achieving a proper production rates for the crews; (4) accounting for transportation of crews; and (5) differing quantities for the associated various units (Stradel and Cacha 1982; Reda 1990; Cole 1991; Rahbar and Rowings 1992; Suhail and Neale 1994; Harmelink 1995; El-Rayes and Moselhi 1998; Hegazy and Wassef 2001; Yamin and Harmelink 2001, Mattila and Park 2003; Huang and Sun 2006; Hegazy and Kamarah 2008; Zhang et al. 2013). Nevertheless, network scheduling techniques are flexible and can be easily integrated into optimization models. Different optimization models were integrated into the traditional network techniques to optimize the developed schedules to meet the linear infrastructure projects properties (Chan et al. 1996; Ipsilandis 2007; Ammar 2013).

On the other hand, previous research developed a number of resource driven scheduling approaches (i.e. Line of Balance, Linear Scheduling Methods, Repetitive Scheduling Method) to overcome the traditional network scheduling techniques drawbacks. The developed resource driven scheduling models attempt to determine the optimal number of construction crews per activity that enables the project to complete within the desired duration, within budget and with

minimal work interruptions. Nonetheless, the aforementioned scheduling techniques has certain drawbacks: (1) fixed production rates based on pre-execution information that ignores other production rates that can generate better schedules (Roofigari-Esfahan et al. 2015); and (2) inability to, independently, optimize different parameters simultaneously. As such, the resource driven techniques were not well received by the practitioners.

The following subsections illustrate the different parameters investigated by the recent research, either tackled via resource driven schedules, or through the optimization of network scheduling techniques.

### ***Work continuity and production rate variability***

In LIPRA, resources move from one unit to the other, repeating the same sets of tasks. As such, resources optimal utilization is crucial in linear infrastructure projects (Ioannou and Yang 2016). In fact, this concept led to the development of various resources driven scheduling techniques (i.e. Line of Balance, Linear Scheduling Methods, and Repetitive Scheduling Method). Furthermore, other various scheduling optimization models considered such parameter for optimization or as a scheduling constraint (El-Rayes and Moselhi 2001; Hyari and El-Rayes 2006; Huang and Sun 2006; Vanhoucke 2006; Ipsilandis 2007; Elbelatgi and ElKassas 2008; Maravas and Pantouvakis 2011; Huang et al. 2016).

The work continuity is affected by the rate of progress of each activity, and correspondingly the production rate of the construction crews. Resource driven schedules (i.e. Line of Balance and Linear Scheduling Method) assume fixed production rates across the different construction crews. This is not always practical as the production rates of the construction crews vary depending on their composition, their stochastic nature and the construction site conditions (Duffy et al. 2011). As such, previous research addressed the effect of variation in production rates on the work continuity through resource driven scheduling techniques. In parallel, further development was carried out in the optimization of traditional network scheduling techniques to account for the effects of the production rates of the construction crews on the work continuity of repetitive activities projects (Moselhi and Hassanein 2003; Duffy et al. 2011; Maravas and Pantouvakis 2011). Sacks et al. (2017) proposed a Construction Flow Index that can be integrated into the infrastructure planning and scheduling to uphold the production flow in a

construction project. Dolabi and Afshar (2016) developed a max–min ant system model to address the needs for changing the production rates of crews to maintain work continuity. Duffy et al. (2011) suggested a novel approach in developing repetitive activities projects schedules with varying production rates for the construction crews. Hsie et al. (2009) presented a resource constrained scheduling model for infrastructure projects that addresses work continuity of activities via an evolutionary algorithm while maintaining lead times between activities.

### ***Transportation of resources***

After the completion of one unit in an activity, the construction crews and resources need to be transported from the current unit to the following one. Combined with mobilization and demobilization cost and transportation duration and cost, resources transportation significantly affects the linear infrastructure projects (Moselhi and Hassanein 2003). The transportation duration is affected by the distance travelled between units and the travelling speed of the construction crews. Such factors are unit and crew dependent as obstacles and distances vary between units, and the travelling speed of the crews depends on their constituents (Moselhi and Hassanein 2003). As such, both resource driven schedules as well as optimized network scheduling techniques considered the optimization of resource transportation cost and time from one unit to the other (Moselhi and Hassanein 2003; Huang and Sun 2006; Huang et al. 2016). The aforementioned research focussed on the travelling distance between units, their corresponding costs per construction crew, and the obstacles that hinders the transportation of resources.

### ***Time-cost trade-off***

Decreasing the total project cost and duration is one of the most intensely researched aspects in construction projects scheduling. In linear infrastructure project scheduling, the time-cost trade-off was researched through optimized traditional network models and resource driven schedules that might compromise them to work continuity (Huang and Sun 2006; Hyari and El-Rayes 2006; Senouci and Al-Derham 2008; Lucko 2011; Ioannou and Yang 2016). Through the last decade, research focussed on managing the project cost and duration through dynamic programming (Moselhi and Hassanein 2003; Fan and Lin 2007), and evolutionary algorithms (Hegazy and Wassef

2001; Leu and Hwang 2001, Hegazy et al. 2004, Hyari and El-Rayes 2006, Elbelatgi and ElKassas 2008; Senouci and Al-Derham 2008; Moon et al. 2015). In spite of the undoubted usefulness of the aforementioned models, they did not consider simultaneous optimization of such problem with other factors through LIPRA schedules. The utilized optimization approaches were able to search the vast solution space but may fail to determine a global optimal solution due to the utilized single evaluation functions.

### **Units delivery delays**

In LIPRA, meeting delivery dates of project's units is an important issue to satisfy the requirements of the owner. Delivery delays are one of the major disputes between the owner and contractor. Some might argue that this is a local problem that can be handled by planners or project managers. However, if it is not properly accounted for at the scheduling level, it will negatively affect the contractor's cash flow, and ultimately project's performance. Nevertheless, few attempts were carried out to explicitly research units' delivery delays in LIPRA. Ipsilandis (2007) developed a multi-objective model for linear projects scheduling with repetitive activities that minimize the unit delivery delays among other parameters.

### **Knowledge gap**

The aforementioned LIPRA parameters have been optimized through the last decade via resource driven scheduling techniques and through the optimization of traditional network scheduling techniques. Nonetheless, the previous well recognized researches lack the ability of pure simultaneous optimization because they utilize a single objective function to optimize either project duration, work continuity, total cost, or various combinations. This limits the comparison of the different tradeoffs and the identification of alternative solutions. Thus, there is a need for a multi-criteria simultaneous optimization model for LIPRA scheduling that provides the decision makers with a broad-spectrum of optimal schedules.

### **Research methodology**

The methodology utilized to attain the goal and objectives of this study is comprised of four inter-dependent steps: (1) developing a heuristic scheduling module, that integrates resource driven concepts into the traditional network scheduling techniques, while

taking into consideration the special nature of construction projects with repetitive activities (i.e. transportation of construction crews, distances between units, different quantities in each unit ... etc.). Accordingly, the developed scheduling module will be validated through various numerical examples to evaluate the schedule output (i.e. duration, cost, ... etc.); (2) applying a multi-criteria optimization technique that can simultaneously optimize the multi-objective scheduling problem. Such technique should be able to generate a number of non-dominated schedules that does not compromise one objective over the others; (3) integrating the model with a commercial project management software. As such, the proposed model can be easily utilized by practitioners; and (4) applying the developed model on two case studies for comparison purposes. The authors collected the data for the case studies from well-recognized peer reviewed papers by Hyari and El-Rayes (2006) and Moselhi and Hassanein (2003). This includes the problem statement, activity types, units, quantities and production rates of the construction crews.

## **Model development**

### **Scheduling module**

In developing schedules for projects with repetitive activities, planners usually explore how the selection of different crews – with different production rates – can affect the duration for the different activities (i.e. units or segments). In other words, by assigning different combinations of production rates to different activities through selection of different crews, multiple potential schedules are developed that the planner can choose from based on the project characteristics. Accordingly, in the proposed scheduling module, each activity ( $i$ ) has a number of activity-specific construction crews ( $m$ ) that can be assigned to the various units ( $j$ ) of the activity. Each construction crew has a different production rate and cost to carry out the different activities depending on the crew's specialties constituent. To this effect, the scheduling module consists of four coherent stages that aim to create a schedule depending on the assigned crews to the different activities in each unit. The scheduling module also calculates total project duration, total project cost, total project crews' interruptions and total units' delivery delays. This module involves the following steps as illustrated in Figure 2.

### **Calculating the scheduling dates of the activities**

This step determines the activity's start ( $S_{i,j}$ ) and finish ( $F_{i,j}$ ) dates depending on the assigned construction



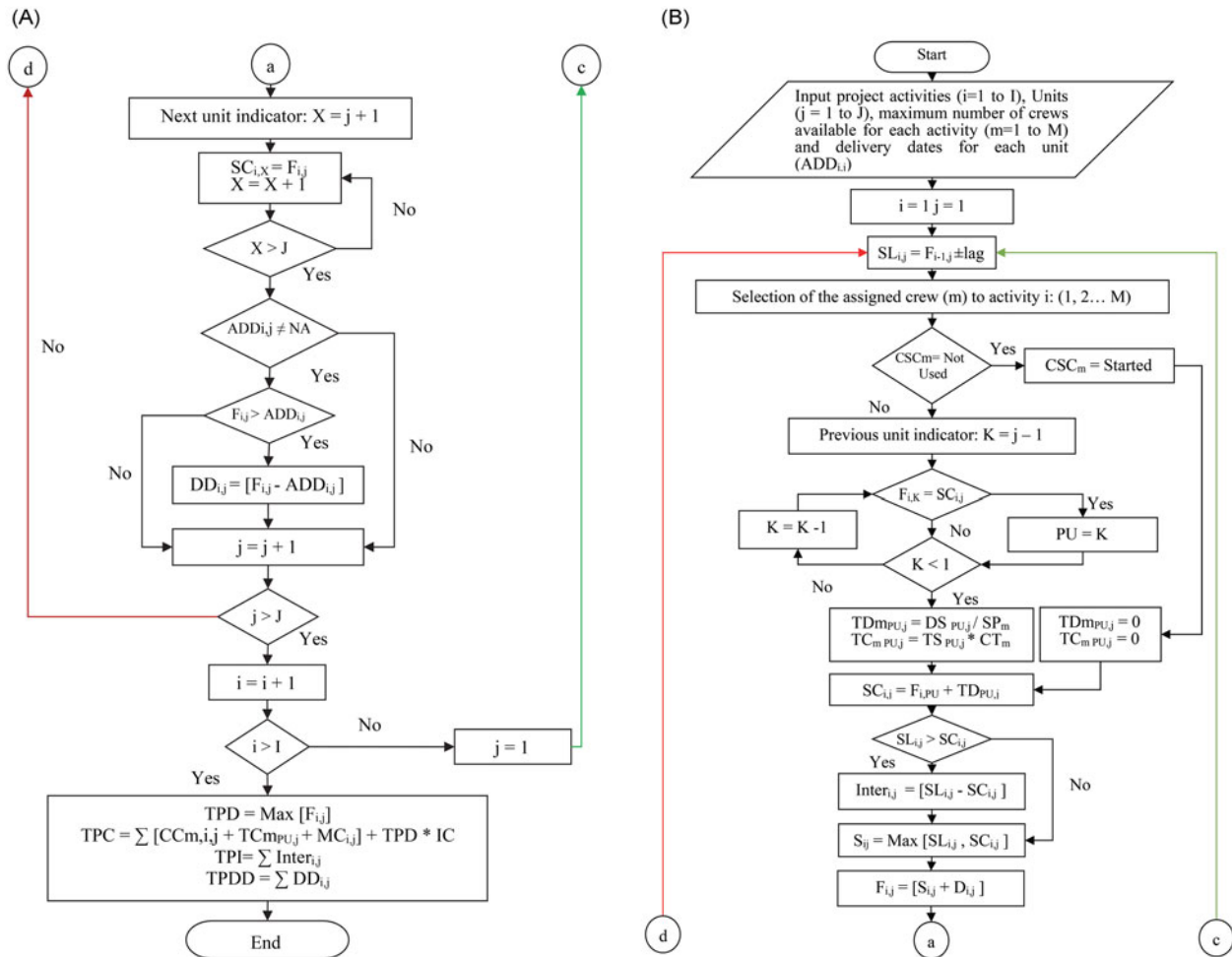


Figure 2. Scheduling module flow chart.

crew and the logical relationship with preceding activities. The start date ( $S_{i,j}$ ) is obtained using Eq. (1) by determining the latest of both logical relationship start date ( $SL_{i,j}$ ), calculated from a regular CPM calculations in Eq. (2), and the earliest possible start date of the crew ( $SC_{i,j}$ ).

$$S_{i,j} = \text{Max}[SL_{i,j}, SC_{i,j}] \quad (1)$$

$$SL_{i,j} = F_{i-1, j} \pm lag \quad (2)$$

The crew  $m$  earliest possible start ( $SC_{i,j}$ ) is obtained through determining the previous unit's ( $PU$ ) finish date ( $F_{i,PU}$ ) that the crew have been assigned at, and its corresponding transportation duration ( $TD_{m,PU,j}$ ) to the current unit. As such, the crew's earliest possible start date can be obtained using Eq. (3).

$$SC_{i,j} = F_{i,PU} + TD_{m,PU, j} \quad (3)$$

Depending on the production rate of the assigned crew ( $m$ ) and the quantities of work to be undertaken, the duration of the activity can be calculated

using Eq. (4). This captures the production rate variation among the various crews,

$$D_{i,j} = Q_{i,j} / P_{m,i} \quad (4)$$

where  $D_{i,j}$  is the duration of activity ( $i$ ) in unit ( $j$ ),  $Q_{i,j}$  is the quantity of work of activity ( $i$ ) in unit ( $j$ ), and  $P_{m,i}$  is the production rate for crew ( $m$ ) that can be assigned to activity ( $i$ ). Accordingly, the finish date is calculated as shown in Eq. (5).

$$F_{i,j} = [S_{i,j} + D_{i,j}] \quad (5)$$

#### Identifying crew's previous unit

Identifying the  $PU$  that the construction crew ( $m$ ) has been working at helps determining the transportation duration ( $TD$ ) and cost ( $TC$ ) for the assigned crew. The  $PU$  is obtained through: (1) determining if the assigned crew ( $m$ ) have been working at any unit before the current one using a crew start check index ( $CSC_m$ ) and (2) if the previous step is true (started) then via backward checking through the finished

units, the model determines the  $PU$  of the construction crew ( $m$ ).

### Transportation duration and cost

Transportation from one segment (i.e. unit) to another can be critical in terms of duration and cost. This is amplified if the crew depends on heavy equipment and the construction site is formed of distributed work areas or segments. Thus, the transportation duration and cost must be calculated according to the assigned construction crew ( $m$ ) and its  $PU$ . And since each two segments have different distances, in addition to different speeds for each crew, there will be different transportation duration ( $TD$ ) and cost ( $TC$ ). The transportation duration of any crew ( $m$ ) is obtained through Eq. (6).

$$TD_{mPU,j} = DS_{PU,j}/SP_m \quad (6)$$

where,  $m$  is the assigned construction crew,  $j$  is the current unit, ( $PU$ ) is the previous unit, ( $DS$ ) is the distance to be travelled by the crew ( $m$ ) from one unit ( $PU$ ) to the other ( $j$ ), and ( $SP$ ) is the average speed of the construction crew ( $m$ ).

The transportation cost ( $TC_{mPU,j}$ ) of any crew ( $m$ ) from one unit ( $PU$ ) to the other ( $j$ ) is obtained using Eq. (7).

$$TC_{mPU,j} = DS_{PU,j} \times CT_m \quad (7)$$

where, ( $CT$ ) is the transportation cost of the construction crew ( $m$ ) per unit distance.

### Adjusting the crew's available start dates in the upcoming units

After scheduling an activity ( $i$ ) in unit ( $j$ ) using the assigned construction crew ( $m$ ), the earliest possible start dates for the following units for the same activity using the same construction crew should be adjusted. The adjustment is obtained through checking the upcoming units ( $j+1, j+2, \dots, J$ ) of the same activity type using the same crew ( $m$ ) and changing their corresponding earliest possible start date ( $SC_{i,j+1}, SC_{i,j+2}, \dots, SC_{i,j}$ ) to the finish date of the current activity ( $F_{i,j}$ ).

At this point, the scheduling module have created a practical plan that takes into consideration the production rate of the assigned crew, its transportation duration and cost, detection of the previous unit that the crew has been working on, and changing the crew's earliest possible dates for the same activity in the next units. To this effect, the scheduling module can calculate:

**Total project duration.** The total project duration ( $TPD$ ) equals the maximum finish date of the last activity in each unit (Eq. (8)).

$$TPD = Max [F_{i,j}] \quad (8)$$

**Total project cost.** The total project cost ( $TPC$ ) consists of three parts: construction crew (labor, equipment and materials) cost, transportation cost and indirect cost. The construction crew cost and transportation cost are unit dependent, while the indirect cost is a duration dependent as shown in Eq. (9).

$$TPC = \sum_{m=1}^M \left[ TC_{mPU,j} + \sum_{i=1}^I \sum_{j=1}^J CC_{mi,j} \right] + TPD \times IC \quad (9)$$

where, ( $CC$ ) is the construction crews ( $m$ ) cost assigned to activity ( $i$ ) in unit ( $j$ ), and ( $IC$ ) is the indirect cost per day.

### Total project interruptions due to resource idle time

Interruptions may occur due to the difference between the logical start time ( $SL_{i,j}$ ) and the crew's earliest possible start date ( $SC_{i,j}$ ). These interruptions need to be calculated and minimized (through the optimization module) to increase the utilization of resources. Also, interruptions are only found when the resources are idle, and not being used or undertaking activities. The module first checks if there were interruptions in the first place, and then calculates the interruptions as per Eq. (10).

$$Inter_{i,j} = \begin{cases} SL_{i,j} - SC_{i,j} & \text{if } SL_{i,j} > SC_{i,j} \\ 0 & \text{Otherwise} \end{cases} \quad (10)$$

where  $Inter_{i,j}$  is the interruption of activity ( $i$ ) at unit ( $j$ ).

The total project interruption is calculated using Eq. (11).

$$TPI = \sum_{i=1}^I \sum_{j=1}^J Inter_{i,j} \quad (11)$$

### Total project units delivery delays.

Meeting delivery dates of project's units is an important issue to achieve project objectives. Thus, the scheduling module checks if there's a required finish date for each activity. If true, then it calculates any delivery delays (as shown in Figure 2), where,  $ADD_{i,j}$  is the required delivery date of activity ( $i$ ) at unit ( $j$ ),  $DD_{i,j}$  is the delivery delay for activity ( $i$ ) in unit ( $j$ ) and equals  $[F - ADD]$ . The total project delivery delay is then calculated (Eq. (12)).

$$TPDD = \sum_{i=1}^I \sum_{j=1}^J DD_{i,j} \quad (12)$$

### Multi-criterial optimization module

The proposed scheduling module formulation is suitable for generating repetitive activities projects' schedules depending on the construction crews allocation to the activities in the different units. Each construction crew allocation produces a new schedule for the LIPRA as each construction crew has its own production rate, direct cost, and available start date. Thus, the number of variables for each solution (i.e. crew allocation) is  $I^*J$ , where  $I$  is the number of activities and  $J$  is the number of units. To this effect, there will be a large number of feasible solutions or crews allocations ( $M^{I*J}$ , where  $M$  is the number of crews) with different combinations of construction crews that are assigned to different activities. For example, a project consisting of five activities repeated over four units will produce twenty variables. Assuming four construction crews available for each activity, this will result in a solution space of  $4^{20}$  possible schedules. Thus, a rigorous optimization tool is necessary to determine the near-optimum set of schedules from this vast feasible region.

In order to achieve the aforementioned goals and objectives, Genetics Algorithms (GAs) is utilized. GAs showed great efficiency in searching for global optimum solutions for complex problems (Li and Love 1997; Feng et al. 1997; Hegazy and Ayed 1999; Elbeltagi et al. 2005; Hyari and El-Rayes 2006; Eid et al. 2015; Eid and El-adaway 2017a, 2017b, 2017c). GAs is inspired by biological systems' improved fitness through evolution and Darwin's theory of natural selection and the survival of the fittest (Holland 1975). GAs forms a set of random solutions that search the solution space for the near-optimum set of solutions through evaluating and evolving the solutions depending on their fitness. The solutions in GAs are called chromosomes, and each chromosome consists of numbers of genes which carry the values of the problem's decision variables (Elbeltagi et al. 2010). These solutions are subject to evolution, mimicking nature, through crossover of inherited genes – from parents to offspring – and, occasionally, through mutation (sudden change in a gene's value). Crossover and mutation processes are controlled by the crossover and mutation probabilities. Being a common natural process, crossover probabilities are traditionally given a rate that ranges between 0.6 and 1.0 (Elbeltagi et al. 2005). In contrast, mutation is far less likely to occur in nature, and usually given a probability rate around 0.1. It should be noted that the selection of the values for crossover and mutation indices depends on the problem domain and solution

space to allow for exploration of the feasible solutions and exploitation of the optimal schedules (Lim et al., 2017).

In the proposed model, each solution (i.e. crews allocation that reflects a new schedule) is represented by a chromosome of length  $I^*J$ . Each gene in the chromosome represents an activity ( $i$ ) in a specific unit ( $j$ ), while the gene's value (i.e. optimization variables) represents the crew assignment ( $m_{i,j}$ ) as shown in Figure 3. The gene's value is restricted to the lower and upper bounds of the available number of crews per activity type. Thus, the chromosome represents a solution for assigning the available crews throughout the repeated activities of the project. Such allocation can then be evaluated using the proposed scheduling module to determine the start and finish dates of the activities.

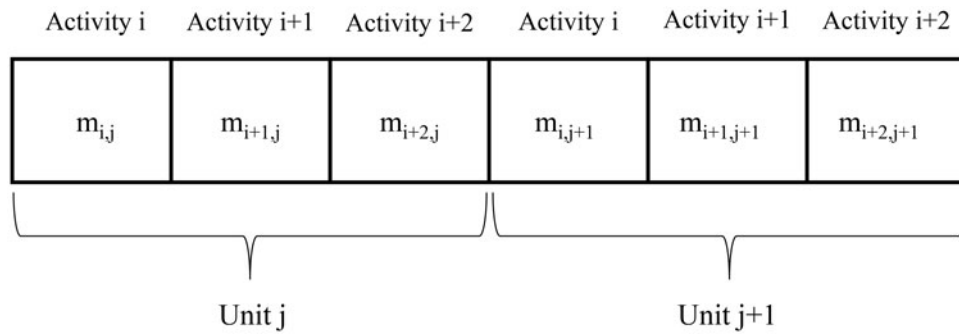
In addition to the optimization variables, the GAs optimization model requires identifying the objective function and the optimization constraints. The objective functions are (1) minimize total project duration; (2) minimize total project cost; (3) minimize total project interruptions; and (4) minimize total project units' delivery delays. These objective functions are all calculated from the scheduling module for each chromosome, as mentioned in the previous section. The solutions (i.e. schedules) are evaluated through these multiple objective functions as given in Eq. (13).

$$\left. \begin{aligned} \text{Min. Total Project Duration: } & \text{Max}[F_{i,j}] \\ \text{Min. Total Project Cost : } & \text{TPC} = \sum_{m=1}^M \\ & [TC_{mPU,j} + \sum_{i=1}^I \sum_{j=1}^I CC_{mi,j}] + \text{TPD} \times \text{IC} \\ \text{Min. Total Project Interruptions:} & \\ & \sum_{i=1}^I \sum_{j=1}^I \text{Inter}_{i,j} \\ \text{Min. Total Project's Units' Delivery Dates Delays:} & \\ & \sum_{i=1}^I \sum_{j=1}^I DD_{i,j} \end{aligned} \right\} \quad (13)$$

Moreover, the following three constraints are introduced to keep the solutions (i.e. schedules) feasible:

- 1) The indices ( $m$ ) for the various construction crews are limited to the positive integer number of crews available to each activity;
- 2) The actual number of crews used in each activity is limited to the number of repetitive units; and
- 3) The start time of an activity must be greater than or equal to the finish date of its predecessor.





**Figure 3.** Illustration for the proposed chromosome structure.

The authors integrated Pareto-Front Sorting (PFS) into the GAs model as a multi-criteria evaluation module (based on the four objectives) to determine the set of non-dominated schedules. PFS identifies a set of non-dominated solutions, which are ranked as the first Pareto Front. Then the process continues to rank the remaining schedules to the second Pareto Front and so on till all the solutions are ranked to their fronts. Consequently, the fitness of any solution equals the inverse of its rank (Beradi et al. 2009; Li and Zhang 2009; Elbeltagi et al. 2010). A solution (i.e. schedule) with a lower-numbered rank is assigned a higher fitness than that for a solution with a higher-numbered rank. To this effect, for a minimization problem, the fitness of each solution  $i$  is calculated by Eq. (14) (Elbeltagi et al. 2010).

$$Fitness_i = 1 / rank_i \quad (14)$$

where  $fitness_i$  and  $rank_i$  are the fitness value and rank number for the solution  $i$ .

The benefit of using GAs, therefore, is to arrive at a near-optimum solution by intelligently searching this large solution space, while PFS allows for representing a broad spectrum of optimal solutions that does not compromise one objective over the others. This approach allows for generating a set of Pareto-optimal solutions. Moreover, such an approach avoids the misguidance due to the utilization of improper weights when using weighted aggregated objective function instead of simultaneously optimizing the four aforementioned objectives.

### Model automation

To facilitate the usage of the developed model, it is implemented on a commercial software, Microsoft Project 2007 (MS Project) that is customary to many construction practitioners. The software provides the

planner with simple data entry of the activities; dependencies, relationships, duration... etc. Also, the software performs CPM calculations on the project as well as representing the project schedule in bar chart and network diagrams. More critical for the implementation of the model on MS Project is that it allows modelling more complex algorithms by programming such algorithms through Visual Basic for Application macro tool (VBA macro). VBA macro allows for altering the schedule of the project depending on the inputs given to the model. VBA macro requires basic programming skills to edit the MS Project calculation process. The utilized source code for the project can be found at the following URL <<https://www.msaeideid.com/s/SouceCode.rar>>.

To start implementing the model on MS Project, the practitioner should start by creating a regular construction plan through data entry of the activities – repeated according to the number of units – along with their relationships throughout the same unit, the quantities per unit and the delivery date if existed. Each of the repetitive activities can have up to four different construction crews. Each construction crew has its own production rate, as well as its direct cost and the available start time to be assigned to the activity and its corresponding units. The data entry allows MS Project to calculate the project duration. When starting the process, the user will be prompted to enter the data presented in Table 1. The model then starts creating initial schedules (solutions), evaluating these schedules and evolving them to reach near-optimum solutions.

### Results and analysis

In order to test the proposed model and demonstrate its capabilities in scheduling and simultaneously optimizing multi-objective LIPRA projects, the model was

implemented on two example projects from the literature to enable comparing the obtained results with those previously reported. This section attempts to demonstrate the model's flexibility and ability to provide a set of near-optimum schedules.

### **Application project 1**

This project is a three-span concrete bridge presented by Hyari and El-Rayes (2006). It consists of five activities; excavation, foundations, columns, beams and slabs that are repeated in four sections. Hyari and El-Rayes (2006) also presented the available crews for such activities, as shown in Table 2. The precedence relationships among these five successive activities are finish-to-start with no lag. It is worth noting that the model under investigation did not take into consideration the transportation duration of construction crews, and only had two objective functions, namely minimize project duration and minimize crews' interruptions. For this reason, and to have equal basis for comparison, the authors neglected from their own model construction crews' transportation durations and costs as well as the objective functions to minimize total project cost and minimize the units' delivery delays. Thus, the objective of this comparison is to demonstrate the proposed model ability to determine a non-dominated set of schedules through achieving the two minimum project duration and minimum work interruption for construction crews.

An initial schedule was created by MS Project after the data entry step; project activities, dependencies, quantities, etc. Afterwards, the optimization module data were introduced as discussed in Table 1. As such, 200 initial random schedules (chromosomes) were created, each with a different distribution of the construction crews across the project's units. The evaluation module then calculated the total project duration and work interruption per schedule. Utilizing Pareto Front sorting, the evaluation module ranked the schedules to the corresponding fronts. To this effect, through crossover and mutation probability indices of 0.85 and 0.2, respectively, the optimization module carried out the GAs evolution processes. It should be noted that the authors experimented with different crossover and mutation indices to determine suitable ones that converge to an optimal solution in a reasonable amount of time.

The results of the proposed model are analyzed and compared to the solutions drawn from the literature by Hyari and El-Rayes (2006). Samples of the Pareto Front solutions (i.e. schedules) are shown in

Table 3, and a comparison for project duration and interruptions is shown in Table 4. The positive differences between the proposed model results and Hyari and El-Rayes (2006) are due to the developed model's ability to use more than one construction crew for the same activity creating flexibility when dealing with large number of repetitive units. Also, through analyzing the results obtained from the proposed model and results by Hyari and El-Rayes (2006), it is observed that the current model's project duration varied between a maximum value of 94 days and minimum value of 91 days, while Hyari and El-Rayes (2006) minimum project duration is 106.8 days and expanded to 117.9 days. However, both models reached a zero work interruption, yet the current model's maximum work interruption is 12 days while Hyari and El-Rayes (2006) work interruption reached 15 days. Figure 4 shows a comparison between the proposed model's results and the results drawn from the literature.

Furthermore, the model's full ability is validated on the same example by optimizing the four objective functions simultaneously; (1) minimization of project duration, (2) minimization of project cost, (3) minimization of project total interruptions and (4) minimization of units' delivery dates delays. The objective of this step is to illustrate the capability of the model in determining a set of near-optimum non-dominated schedules that take into account the previously mentioned various characteristics of LIPRA. However, the example drawn from literature did not consider the project cost; direct cost, indirect cost and transportation cost. The example, also, did not consider the units' delivery dates required. For this purpose, some assumptions have been made to experiment the model by adding costs for the construction crews undertaking each activity, as well as their transportation costs and delivery dates of each activity. Table 5 shows the direct cost of each activity with respect to the different construction crews (i.e. the indirect cost for this experimentation is assumed to be \$200 per day with a population size of 200 and crossover and mutation probability of 0.85 and 0.15, respectively), Table 6 illustrates the assumed distances between repetitive units in KM, and Table 7 shows the assumed speeds and costs for each construction crew. The change in the mutation index here, in comparison to the previous example, is a result of multiple trials by the authors to get the model to converge to an optimal solution in a reasonable amount of time.

The Pareto near-optimum solution set expanded to 121 near-optimum solutions. A quick comparison

**Table 1.** Project data entry.

Module	Input	Objective
Scheduling	Number of activities	Project initialization
	Number of units	Project initialization
	Activities dependencies	Project scheduling
	Project indirect per day and material cost	Project cost calculation
	Number of crews, production rates and cost	Project scheduling and cost calculation
	Transportation distance between units	Crews transportation duration and cost
	Transportation cost for each crew	Crews transportation duration and cost
Optimization	Initial population size	Optimization initialization
	Crossover and mutation probabilities	Optimization evolution

**Table 2.** Application project 1 quantities of work and available crew options.

Activity	Excavation				Foundation				Columns				Beams				Slabs							
Units	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
Quantity of Work (m <sup>3</sup> )	1147	1434	994	1529	1032	1077	943	898	104	86	129	100	85	92	101	80	0	138	114	145				
Available Crews	1				1				2				3				4							
Production Rate (m <sup>3</sup> /day)	91.75				89.77				71.81				53.86				5.73				6.88			

between selected 10 Pareto near-optimal solutions' relative costs, duration, delivery delays and crews' interruptions are shown in Figure 5 on a radar chart. It can be noticed that the relative variance in schedules' costs and durations is not as significant as the units' delivery delays and crews' interruptions. Schedule number 10 in the chart shows the least delivery delays for the units, however, it corresponding project cost is relatively high. Likewise, schedules 6 and 7 show a significant reduction in work interruptions but on the expenses of delivery dates of units and no significant reduction in duration or cost. Figure 5 supports the claim on the need to develop multiple optimal schedules that provide the decision makers with a broader spectrum of schedules that meet the requirements of the evolving project.

### Application project 2

For further testing, another example of a highway project drawn from the literature (Moselhi and Hassanein 2003) is analyzed. The project involves the construction of a three-lane-highway of stretch of 15 km and consists of five activities. The project is divided into 15 repetitive units each of length 1 km and each of the five activities is repeated at each of the 15 segments or units of the project. The precedence relationships among these sequential activities are finish-to-start with no lag time. Three alternative construction crews were introduced into the model; each represents different production rates. This approach gives the planner flexibility in creating alternative construction crews by changing one of the crews and checks which schedule is suitable to the project that takes into consideration the relationship between time, cost and interruption. To investigate

other options, a \$3000/day indirect cost is assumed and a set of delivery dates for the 'Grub and Remove Trees' activity at the 9th and the 15th units are assumed to finish at 35 and 87 days, respectively. The model reached a Pareto near-optimum solution set of 16 schedules. Selected schedules from the Pareto near-optimum solutions set are shown in Table 8.

Through the analysis of the model's results in comparison to the model of Moselhi and Hassanein (2003), it is observed that the model minimum duration and maximum total project duration are 88 and 100 days, respectively, while the model of Moselhi and Hassanein (2003) minimum and maximum project duration were 87 and 97 days, respectively. However, the proposed model gave variant schedules with respect to total project cost and respecting the required units' delivery dates while Moselhi and Hassanein (2003) did not. It can be observed that the minimum project duration (88) came with a relatively higher cost as well as the highest units' delivery delays. This is due to respecting the crews' work continuity which delayed the delivery dates of the first units.

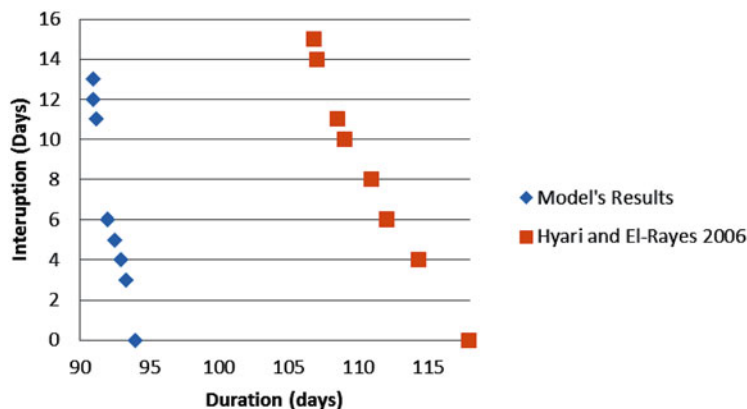
As selecting a single schedule from hundreds of schedules is a difficult task, the authors utilized a compromise solution technique introduced by Grierson (2008) to aid the decision maker with a solution that satisfies all objectives fairly. The model assumes that cost, duration, interruption and delivery dates delays of the units are all equally important. It is acknowledged that this might not be the case on every project depending on projects specific characteristics. However, as such special conditions can only be assessed and prioritized by the stakeholders associated for each project (i.e. which are unknowns at this stage), the authors believe that their assumption is

**Table 3.** Assigned construction crews' indices (m) for each activity of application project 1.

	Schedule1	Schedule2	Schedule3	Schedule4	Schedule5	Schedule6
Excavation1	1	1	1	1	1	1
Foundation1	3	3	3	3	3	3
Columns1	1	2	1	2	1	1
Beams1	3	4	4	4	4	2
Slabs1	2	2	2	2	2	2
Excavation2	1	1	1	1	1	1
Foundation2	2	1	1	3	1	1
Columns2	1	2	3	1	2	1
Beams2	2	4	2	2	2	4
Slabs2	1	1	2	1	2	1
Excavation3	1	1	1	1	1	1
Foundation3	1	1	1	2	1	1
Columns3	3	3	3	3	2	2
Beams3	3	2	3	1	3	3
Slabs3	1	1	2	1	2	1
Excavation4	1	1	1	1	1	1
Foundation4	1	1	1	1	2	2
Columns4	3	3	3	3	3	3
Beams4	1	1	1	1	1	1
Slabs4	1	1	1	1	1	1
Project duration	91	92	92.5	93	93.5	94
Project interruptions	12	6	5	4	3	0

**Table 4.** Results comparison of application project 1.

Comparison element	Proposed model sample solutions						Hyari and El-Rayes (2006) sample solutions					
Project duration	91	92	92.5	93	93.5	94	106.8	107	108.5	110.9	114.3	117.9
Project interruption	12	6	5	4	3	0	15	14	11	8	4	0

**Figure 4.** Comparison of results for application project 1.

acceptable for this stage of model development. Table 9 illustrates the Pareto compromise solution and best alternative for the Pareto near-optimum scheduling set.

## Discussion

As it can be observed through the results obtained from the two aforementioned application projects, the proposed multi-criteria optimization model was able to meet the research goals and objectives. The model was able to simultaneously optimize the four

objectives (cost, duration, interruption and units' delivery delays). Also, the proposed multi-criteria optimization model is able to present a set of non-dominated schedules. Such schedules do not compromise one objective over the others as the model does not employ single aggregated objective function. To this end, the proposed model can present the decision makers with a broad optimal schedule spectrum that would meet the evolving linear infrastructure project needs.

The proposed scheduling approach allowed for assigning multiple crews per activity. Such approach positively impacted the outcome of the projects

**Table 5.** Activities direct costs.

Activity	Repetitive unit	Construction crew1 (\$)	Construction crew2 (\$)	Construction crew3 (\$)	Construction crew4 (\$)
Excavation	1	1000	0	0	0
	2	1200	0	0	0
	3	4700	0	0	0
	4	4700	0	0	0
Foundation	1	3200	3000	2500	0
	2	3400	3100	3000	0
	3	3500	3150	3000	0
	4	3500	3200	3000	0
Columns	1	3700	3900	4000	0
	2	3500	3750	3900	0
	3	4500	3300	3200	0
	4	5000	5200	5600	0
Beams	1	4500	4000	3900	3700
	2	4300	3800	3600	3500
	3	4500	4300	4000	3800
	4	4700	4500	4100	3900
Slabs	1	0	0	0	0
	2	8000	6000	0	0
	3	8100	6500	0	0
	4	8000	6100	0	0

**Table 6.** Distance between repetitive units.

To From	Unit2	Unit3	Unit4
Unit 1	0.5	1	1.25
Unit 2	–	0.5	0.75
Unit 3	–	–	0.25
Unit 4	–	–	–

through providing flexible schedules that maximize the utilization of resources while accounting for the transportation cost and duration that impacts the LIPRA schedules. The scheduling model also accounts for the variation in the production rates across the various crews, as well as their travelling speed and cost. In addition, the model takes into consideration the variation of quantities among the different units. Such scheduling approach attempts to represent practical projects and construction crews that are assumed homogenous in other models.

The optimization model (GAs) showed significant performance in finding optimal solutions for the problem at hand, despite of the vast solution space for LIPRA. Nevertheless, identifying proper crossover and mutation indices that search the solution space efficiently and effectively took the authors multiple attempts. The adequate crossover and mutation indices are problem dependent and requires the practitioners some experience and multiple trials. In addition, to find a compromise solution, the authors utilized an approach that uniformly weighs all the objectives. This might not meet the needs of the practitioners and should be taken into consideration depending on the evolving project.

Even though the model was tested and implements on linear projects to focus the research scope, it can

be applied to non-linear projects as they share most of the repetitive activities projects properties. In addition, the objectives of the proposed model are applicable for non-linear projects.

### Limitations

Despite the model's positive application on the aforementioned case studies, it is still worth highlighting some limitations and suggestions for improvement of the proposed model. The utilized scheduling module assumes only finish to start relationship between the different activities. This does not represent all the construction activities dependencies. Furthermore, the uncertainty of the construction crews' production rates was not addressed in the current model, which might affect the model's outcome. Moreover, the optimization module neither did account for the resource transportation cost and duration separately, nor considered transportation obstacles (for example, rivers and creeks). The order of work throughout the project was not investigated that might create different schedules.

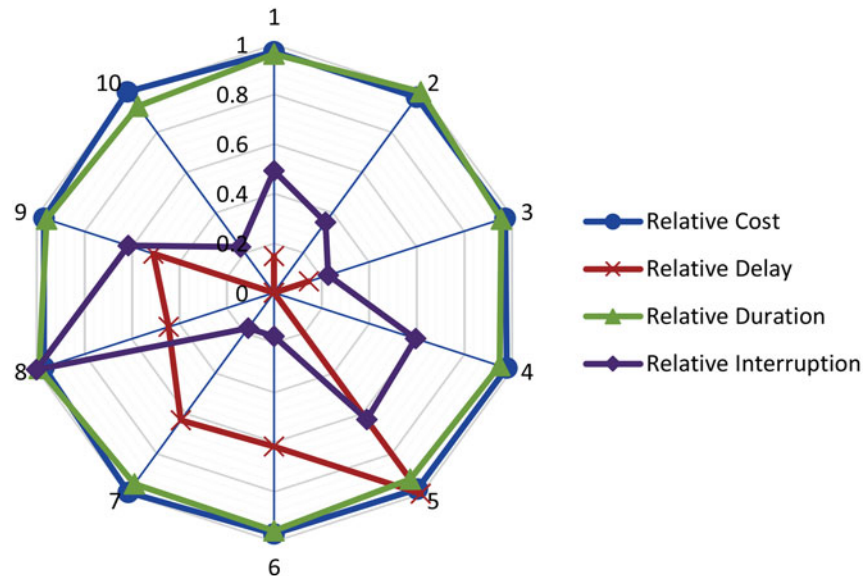
### Conclusion

Previous approaches in optimizing LIPRA schedules lack the ability of pure simultaneous optimization because they utilize a single objective function to optimize either project duration, work continuity, total cost, or various combinations. This limits the comparison of the different tradeoffs and hence, the identification of alternative solutions in cases where the resulting near-optimal schedules cannot be performed in reality due to exogenous factors. In this paper, a



**Table 7.** Construction crews' transportation speeds and cost.

Crews \ Activities	Construction crew1		Construction crew2		Construction crew3		Construction crew4	
	Speed km/day	Cost \$/day	Speed km/day	Cost \$/day	Speed km/day	Cost \$/day	Speed km/day	Cost \$/day
Excavations		1000	N/A	N/A	N/A	N/A	N/A	N/A
Foundations	3	1500	5	1500	5	1300	N/A	N/A
Columns	5	1400	5	1300	6	1300	N/A	N/A
Beams	3	1600	5	1500	5	1500	6	1300
Slabs	3	1300	5	1300	N/A	N/A	N/A	N/A

**Figure 5.** Representation of results for application project 1.**Table 8.** Model results for application project 2.

	Sample schedules outputs								
	1	2	3	4	5	6	7	8	9
Total cost (\$)	1,351,503	1,381,597	1,332,308	1,383,930	1,355,062	1,380,989	1,348,082	1,351,142	1,378,152
Total duration (days)	99	97	89	90	89	95	91	100	88
Total delays (days)	5	7.9	0	0.9	0	1	8.7	0	8.8

**Table 9.** Pareto-compromise and best-alternative solutions for application project 2.

Solution	Project cost (\$)	Project duration (days)	Delivery dates delays (days)
Pareto-compromise solution	1,355,230	88.5	4.4
Best-alternative solution	1,332,308	89	0

multi-criteria approach for simultaneously optimizing linear infrastructure projects schedules is presented. The proposed model (1) accounts for the different repetitive activities projects' needs (crew transportation, flexibility in assigning crews to different units, different crews' production rates, etc.), (2) simultaneously optimizes the different objective functions and (3) outputs a set of non-dominated near-optimal schedules and their corresponding tradeoffs. These set of non-dominated solutions can broaden the planners view and understanding of the schedule to be used for the current evolving project.

The proposed approach utilizes new heuristic procedures, GAs and Pareto front sorting, to provide planners and practitioners with the set of various non-dominated near-optimal schedules along with their corresponding tradeoffs. The optimization module identifies the combination of construction crews that minimize total project cost, total project duration, total project interruptions, and total delays to units' delivery dates through simultaneously optimizing those parameters. The proposed approach does not compromise one of the aforementioned parameters over the other. In fact, the proposed model demonstrated its potential through outperforming two

well recognized techniques in the literature as applied to the very same case studies. Furthermore, the proposed model integrates the resource driven schedules into traditional network tool to take advantage of both models' merits. The model was integrated with MS Project using VBA macro and based on the case studies used for testing. As such, the proposed model can be easily utilized by practitioners, and ultimately guide them to the optimal schedule the evolving linear infrastructure project needs that would significantly enhance the performance of LIPRA.

To this end, the authors believe that the proposed model contributes to the construction industry through providing the planners with a tool that would support them in making an informed decision. The ease of use of the developed model on a commercial planning software and the development of a broad spectrum of optimal schedules for LIPRA would potentially enhance the construction industry in achieving the goals of the projects. Furthermore, the proposed multi-criterial simultaneous optimization approach will add to the body of knowledge through the implementation of such technique to different construction engineering and management fields. Such multi-criteria optimization approach can provide better understanding and solutions for inter-conflicting problems, i.e. sustainable infrastructure development, disaster recovery, etc.

### Future work

In order to enhance and furtherly develop the proposed multi-criteria optimization model, the presented scheduling module needs to be improved through: (1) integrating the different activities relationships in the scheduling model that would represent the various construction activities' dependencies; (2) accounting for the uncertainty in the construction crews' production rates that would affect the activities duration, the project cost, work continuity and units' delivery dates; (3) assimilating non-repetitive activities and repetitive activities in one single model; (4) adding the ability to change the work order among repetitive units; and (5) testing the impact of multi-skilled crews in the scheduling of LIPRA. Furthermore, the future research on the optimization module will undergo experimentation of different evolutionary algorithms optimization techniques, such as Particle Swarm Optimization, Ant Colony and Shuffled Frog Leaping algorithms to discover the solution space more effectively and efficiently. Moreover, rigorous sensitivity analyses on the different optimization parameters (i.e. crossover and

mutation probabilities as well as the associated computational times, etc.), across the different evolutionary algorithms, will be carried out when applied to the optimization model. In addition, numerical examples on the performance of the optimization model will be utilized. To this end, the optimal optimization technique will be utilized as the ultimate approach. Finally, the potential of the proposed model will be furtherly tested through implementing the model on non-linear projects.

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