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EFFICIENT REPETITIVE SCHEDULING FOR SCATTERED REHABILITATION PROJECTS

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Abstract: Efficient delivery of large rehabilitation plans for municipal and provincial projects are very challenging due to the geographical separation between sites, the large degree of work repetition, and the large number of crews that need to be synchronized without interruption. To facilitate efficient scheduling of repetitive and scattered rehabilitation projects, this paper presents an innovative scheduling and cost optimization framework. The scheduling formulation is designed to consider the practical constraints that affect scattered projects, including: (a) quantity of work variations among sites; (b) flexible crew assignment strategies; (c) order of site execution; and (d) and moving time and cost from one site to another. The proposed scheduling model utilizes the Constraint Programing (CP) optimization technology to schedule large-scale projects, considering all constraints. This framework will provide large public organizations such as school boards, universities, and municipalities with an effective planning and scheduling tool that is particularly designed to address the challenges facing their management teams in delivering large scattered infrastructure maintenance and renewal programs. A case study for scattered repetitive project will be used to discuss the essential components of the proposed framework and its optimization benefits.

1 INTRODUCTION

Significant efforts in the literature were dedicated to optimize the allocation of the limited funding resources available for the maintenance and rehabilitation (M/R) of deteriorated infrastructure. Little efforts, however, addressed the implementation and the delivery phase of such projects. Most asset-management systems leave the delivery details to the experience of internal personnel, with little or no decision support regarding the execution sequence, resource utilization, and execution planning (Figure 1). This represents a major challenge that can lead to cost overruns and delays. Often, parts of one year's plan get deferred to subsequent years, and thus, the full benefit of the asset-management process, which is a costly process, does not materialize.

Figure 1: Execution Planning for Scattered Repetitive Projects

The delivery planning for infrastructure M/R programs is a challenging process due to the complex nature of infrastructure M/R projects, the need for efficient resource allocation, and the stringent organizational/public/political constraints of public organizations. These projects are repetitive in nature and scattered across large geographical areas (highway sections, bridges, schools, buildings, etc). Within repetitive projects, crews (labor and equipment) move from one unit to the next and complete work that is prerequisite to other successor crews and equipment. Scattered M/R projects are special and complicated type of repetitive projects that requires crews to relocate from that unit to the next. This scattered nature imposes additional challenges in maintaining work continuity and the synchronization between crews at various sites.

Several efforts in the literature have attempted to develop scheduling and cost optimization for the repetitive projects (Suhail and Neal 1994; Hegazy and Wassef 2001; Arditi et al. 2002; Yang and Ioannou 2004; Thabet and Beliveau 1994; Hegazy and Kamarah 2008; Ipsilandis 2007). Because repetitive projects are large, traditional mathematical models may be stuck in local optimum or provide no solution at all (Li and Love 1997; Leu and Yang 1999; Cheng and Ko 2003). Thus, several efforts in the literature have used non-traditional Artificial Intelligence optimization techniques such as Genetic Algorithms (GAs). These efforts include (Leu and Yang 1999; Zheng et al. 2004; Senouci and Eldin 2004). GAs have good capabilities for scheduling and optimizing construction projects, however, take unreasonably long time to provide solution. Kandil and El-Rayes (2005), for example, have reported GAs processing time of 55 hours for a case study of 360 activities, which was reduced to 9.3 hours using a system of parallel computing with 50 processors. Because scattered repetitive projects are large in size and consist of hundreds of activities, using GAs can be very time consuming and many not lead to global optimum.

Recently, Constraints Programming (CP) has emerged as powerful advanced mathematical technique for solving large scale combinatorial problems. It combines logic programming and operations research techniques. In CP, constraints are used as they are in conventional programming to test the validity of possible solutions (Chan and Hu 2002). Thus, CP has recently been used in a wide range of businesses and industries including manufacturing, transportation, health care telecommunications, financial services, energy and utilities. Chan and Hu (2002) used CP to optimize the pre-cast production for concrete pre-cast plant. Tang et al. (2014) utilized CP to develop scheduling and control model for railway projects. Liu and Wang (2007) optimized the resource assignment for to linear construction projects using CP. Despite the many interesting efforts in repetitive scheduling and optimization, special consideration for the challenges of scattered repetitive projects still need to be considered in the advanced CP optimization technique, which is the objective of this research. The paper first discusses the practical challenges encountered by public organizations in delivering their M/R programs. It then introduces a new model to schedule and optimize the scattered repetitive infrastructure M/R projects and uses a case study to demonstrate its functionality and future improvements.

2 EXECUTION PLANNING FOR SCATTERED REPETITIVE PROJECTS

Scattered projects have a very challenging nature. Local conditions such as weather, by-laws, and traffic conditions vary from one site to the other. Therefore, the work at each site should be scheduled when it has maximum productivity. In addition, the sequence (order) of crew movement from one site to another needs to be properly planned to consider the time and cost of transporting resources from one site to the other. Interruption to facilities' operation must be minimized, which imposes tight deadlines challenge to complete these projects. For example, the M/R program for schools and universities must be completed within the short summer break. To meet deadlines, speedy delivery options (often expensive such as overtime or weekend work) need to be considered. In addition, these projects require extensive level of control in regards to scope development, design, tendering, supervision, change orders management, dispute resolution, and cash flow management. The larger the number of facilities involved in an M/R plan, the larger the challenge. Yet, this also represents an opportunity to benefit from repetition if a crew's work is scheduled without interruption to benefit from the learning effect. As such, the need has emerged for more thorough analysis of infrastructure delivery plans that relate specifically to scattered infrastructure projects in terms of the number of crews to use, the construction methods to employ in each activity, the varying work conditions at each site, and the site's execution order.

To address thee above challenges, a proposed schedule optimization model has been developed. The proposed model utilizes CP to determine the optimum construction cost for this type of projects. The mathematical formulation of the proposed model determines the number of crews, and method of construction used in each repetitive activity so that work continuity is maintained, resource limitations are observed, proper site order is selected, and a pre-specified deadline is met. The scheduling formulation involves three aspects: (1) Crew synchronization to meet project deadline; (2) Formulating practical schedule constraints for scattered projects; and (3) Large-scale CP optimization. These are discussed in the following subsections.

2.1 Formulation for Crew-Work Synchronization

For flexibility, and to provide options for cost and time optimization, the scheduling model allows activities to have several construction methods (from cheap-and-slow to fast-and- expensive). Accordingly, each activity will have various construction options with their associated resources, durations, and costs. The basic scheduling algorithm first calculates the duration d_{ijk} that a crew takes to complete the quantity of work Q_{ijk} for activity (*i*) in a typical site (*k*) using construction method (*j*) as follows:

[1] $d_{ijk} = Q_{ijk} \, / \, P_j \, x \, f_{kL}$

The P_j is production rate for the resources involved in method(*j*); f_{kL} is the productivity factor (0 to 1), depending on the working conditions at site (*k*) during month (L). Direct costs are then calculated as follows:

[2] $C_{ijk} = d_{ijk} \, x \, C_{ij}$

Where; C_{ijk} is the direct cost of activity (*i*) using method (*j*) at site (*k*); C_{ij} is the sum of the cost per day. The productivity factor (*f*) adjusts the duration estimate for an activity to account for practical factors that describe the environment (e.g., weather related factors) under which the work to be performed (Hegazy and Kamarah 2008). Since each repetitive site has a network of activities, the CPM technique becomes necessary to calculate the total duration and the activity times for a typical site. Based on activities' durations, the critical path duration ($T1$) of a typical site, as well as the total float (T_{Fi}) of each activity (*i*) are then calculated. Afterwards, the desired progress rate (R_i) needed for any repetitive activity (*i*) with a total float (T_{Fi}) can be calculated based on a given project deadline (T_{DL}) as follows:

[3] $R = (n - 1) / ((T_{DL} - T_1) \; + \; T_{Fi} \;)$

Given the calculated progress rate(R_i), the required number of crews for any activity (*i*) to achieve a required progress (R_i), given its duration d_{ij} that a crew takes to finish one site without interruption(i.e., work continuity and crew synchronization are maintained), using construction method (*j*), is calculated as follows:

[4] $Cr_i = Round \; Up \; (R_i \, x \, d_{ij}), \quad Round \; Up \; (Cr_i); Cr_{ai} \; \leq Maximum \; Available \; Crews$

More information about the basic repetitive scheduling can be found in Hegazi (2002).

2.2 Formulating Practical Constraints for Scattered Repetitive Projects

To consider for the practical conditions for scattered repetitive projects, the following constraints have been considered in the scheduling formulations of the model: (a) Experimenting with variable site order; (b) Accommodating variations among repetitive sites; and (c) using flexible crew assignment strategies. These are discussed as follows:

2.2.1 Variable Site Order

Due to the scattered nature of M/R projects, the cost and duration of the moving between sites should be considered in calculating the duration and cost of scattered projects. An important aspect in assigning resources efficiently is to determine the optimum site execution order. This is particularly critical M/R projects as any changes in site order may result in a different project duration and cost (Figure 5). Once the crew Moving Time (MT) and the Moving Cost (MC) are determined and considered in the scheduling and cost optimization process, the effect of varying the site order can be calculated. In each site order, the time and cost to mobilize a crew from one site to the next is a direct function of the distance between the two sites, as follows:

[5] $Moving\ Time\ (MT) = Distance/CrewMoving\ Speed$

[6] $Moving\ Cost\ (MC) = Distance * Crew\ Moving\ Cost\ per\ K\mathrm{m}$

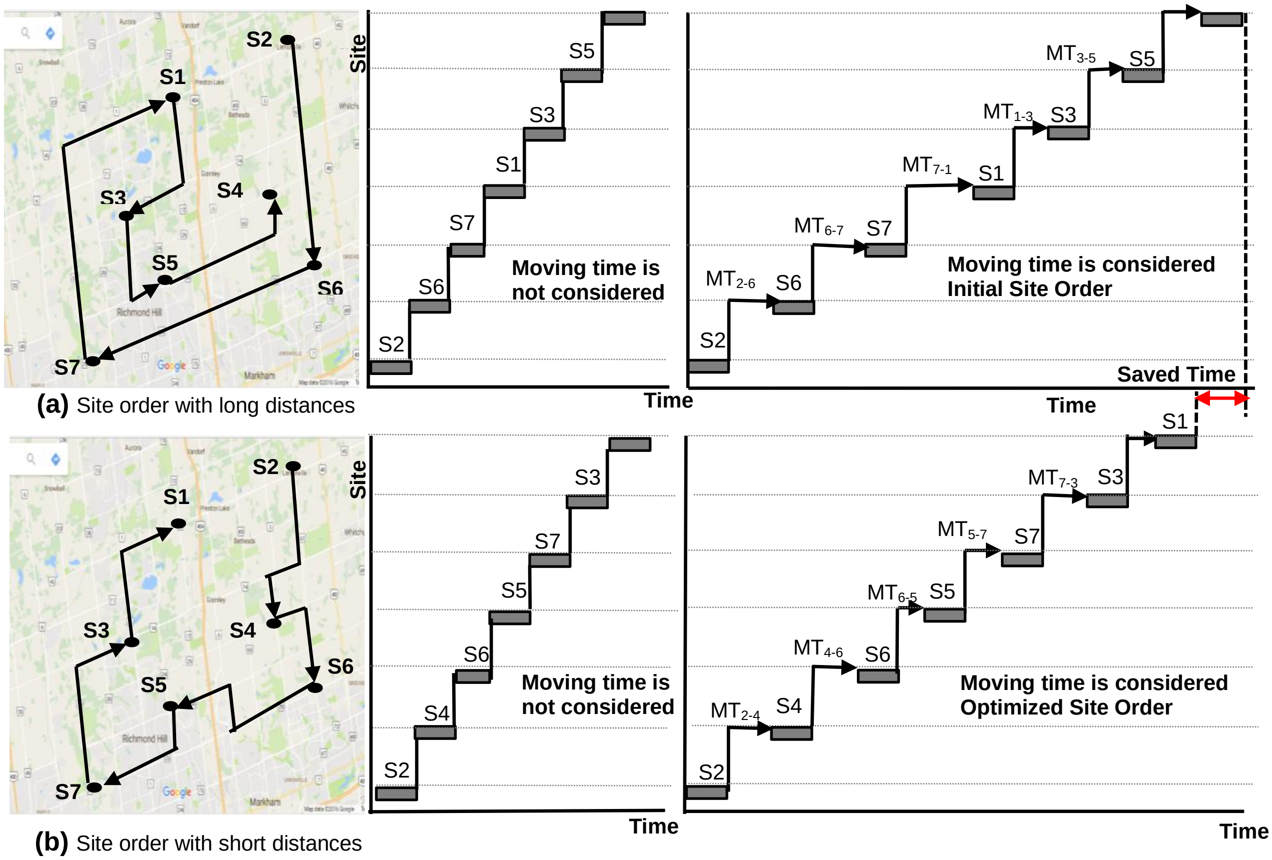


Figure 2: Effect of Changing the Site Order on the Schedule

It is important to note that in the schedule representation of Figure 2, the vertical axis is an index to one of the sites. For example, because the site order in Figure 2 (a) indicates that a single crew moves in the following order (S2 – S6 – S7- S1 – S3 – S5 – S4), as shown on the related map and also indicated on top of each activity bar. Varying the site order to be (S2 – S4 – S6 – S5 – S7- S3 – S1) as in Figure 2b shows a time saving in the schedule due to the smaller moving time between sites. This signifies the importance of site order in the scheduling of scattered sites. One very important consideration in the model formulation is to allow flexibility for having each activity follows its own site order, which has not been addressed in previous studies.

2.2.2 Work Variation among Scattered Site

In a large M/R program, not all sites have the same amount of work for each activity. It is convenient, therefore, to consider that all the identical sites to be “Standard” sites. This will simplify data entry since it is possible to specify the site data once for all the standard sites. Special sites can then be specified separately. When considering each activity at a time, the scheduling model uses the term Standard Site to describe the typical duration and cost of that activity, and the term “Non-Standard” site to describe the duration and cost of any site that differs from the standard as shown in Figure 3. To specify that an activity uses non-standard durations and costs, a simple approach is to allow the user to specify a percentage of the standard site. For example, activity has standard durations at sites 2, 3, and 5. Sites 1 and 4, however has shorter duration, either due to reduced amount of work or increased productivities at these sites

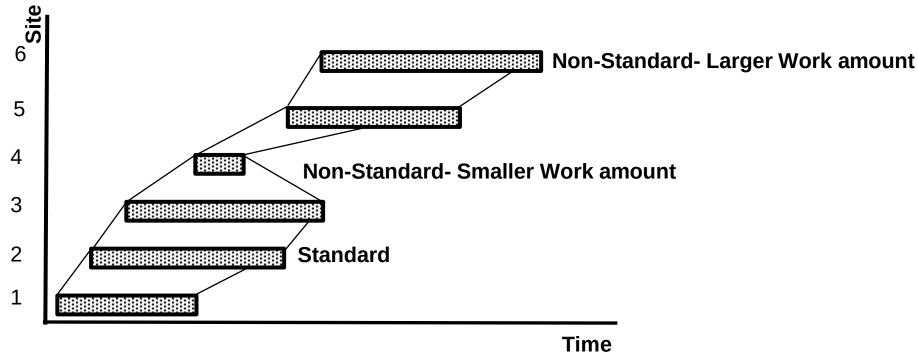


Figure 2: Work Variation among Scattered Sites

2.2.3 Crew Assignment Strategies

To overcome the challenge of different work amount and different productivity among sites, it is advantageous to assign the sites to the first available crew as opposed to the traditional sequential assignment. Figure 4 shows crew1 is assigned to site 5, immediately after it finishes site 4, because other crews are still busy on other sites. This approach has its potential time saving. When crew assignment is known, it becomes possible to consider crew movement time and cost among sites. Using this crew assignment option, detailed start ST and FN times of each activity (i) at any site (k) are calculated as follows:

[7] $ST_{ik} = I + min \sum_{q=1}^{q} CFN_{qp} + MT_{pk} \geq Finish\ Time\ of\ Predecessors$

[8] $FN_{ik} = ST_{ik} + d_{ijk}$

Where, CFN_{qp} is crew finishes time, (q) *is* crew number $\{1,2,..\ Cr_{ai}\}$, (p) is previous site the crew *q* was involved in, (I) is the interruption time, MT_{pk} is moving time from previous site (p) to site (k) (being scheduled), ST_{ik} is the start time for activity (i) at site (k), FN_{ik} is the finish time for activity (i) at site(k) .

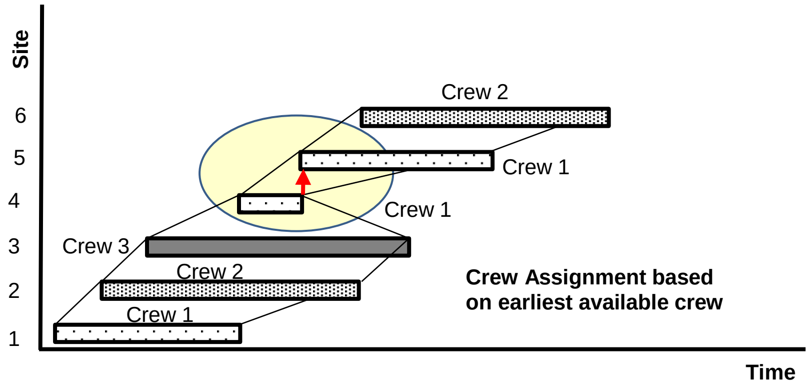


Figure 4: Crews Assignment Strategies

3 SCHDUILING OPTIMIZATION USING CP: A CASE STUDY

The basic scheduling model discussed above is capable of generating schedules by manually changing the options for construction methods, number of crews, and site orders. To program the optimization part of the proposed model, a powerful optimization package called IBM ILOG CPLEX Optimization Studio, incorporating a CP optimizer engine, has been used as it offers advanced features especially suited for scheduling problems. ILOG CPLEX Optimization Studio provides a programming language for describing a problem in terms of variables, constraints, and objective function. In addition, it allows the use of specific constraints that are related to constraint programming and scheduling problems (e.g., a start-to-start logical relationship between two activities). After the model is coded in the specific programming language of the software, the CPLEX-CP solver engine optimizes the problem.

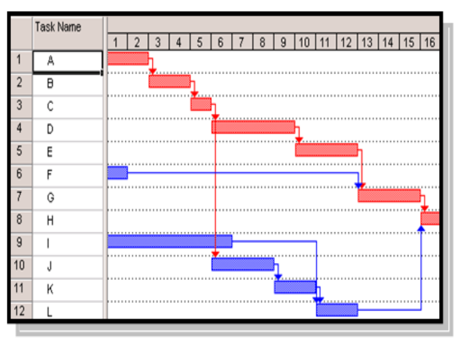
In the CP formulation of the proposed model, the objective function is to minimize the total construction cost by finding the optimum combination of construction methods, number of crews, and site orders that: (a) meet project deadline; (b) maintain work continuity; and (c) consider the scattered projects' constraints. All aspects of the model must be coded in mathematical formulas using the CP language. Full model development is currently on going and represent a substantial task due to large coding efforts needed. As a proof of concept a simpler model with all the above features was developed using the Visual Basic programming language and proved to work efficiently only for small size problems. The extensions to CP will enable large scale optimization.

For experimental purposes, a hypothetical project incorporating 12 repetitive activities along 7 sites is used as a case study. The whole project should be completed within a deadline of 22 working days. The distances among sites were assumed and used in the model. Figure 5 shows the activities information related to three construction methods for each activity, with costs and durations shown. The figure also shows the typical relationships among the activities of a typical site.

No. of Sites = 7; Deadline = 22 working days

Activity	Descriotion	First Estimate Cost1	Dur1	Second Estimate Cost2	Dur2	Third Estimate Cost3	Dur3
1	A	$4,800	Auto 2.0	$1,230	Auto 6.0	$3,000	Auto 1.0
2	B	$4,499	5.0	$5,599	4.0	$2,000	1.0
3	C	$1,000	1.0	$1,000	1.0	$1,000	1.0
4	D	$1,000	4.0	$2,000	3.0	$3,000	2.0
5	E	$1,000	3.0	$2,000	2.0	$3,000	1.0
6	F	$1,000	1.0	$1,000	1.0	$1,000	1.0
7	G	$1,000	3.0	$2,000	2.0	$3,000	1.0
8	H	$1,000	1.0	$1,000	1.0	$1,000	1.0
9	I	$1,000	6.0	$2,000	5.0	$3,000	3.0
10	J	$1,000	3.0	$2,000	2.0	$3,000	1.0
11	K	$1,000	2.0	$1,000	2.0	$2,000	1.0
12	L	$1,000	2.0	$2,000	1.0	$2,000	1.0

12 repetitive activities and their optional estimates



Activity relations

Figure 5: Activities' Costs, Durations, and

The calculated project duration before optimization was 26 days. The optimization model was then used to arrive at the optimum combination of construction methods and site orders to provide a schedule that meets the deadline with minimum cost. The model produced a schedule of 21 days that meets the deadline. Figure 6 shows the initial schedule (on top) and the after-optimization schedule (bottom). It is noted that the site order has been changed in the optimized schedule, as well as the number of crews used (color-coded).

Based on the initial model formulation and results, some comments on the developments made are as follows:

- The model is flexible enough to accommodate several practical considerations encountered by public organizations in delivering their maintenance and renewal programs;
- The model minimizes the total construction cost comprising direct cost, indirect cost, liquidated damage cost, and incentive cost;
- The model considers crew synchronization, work continuity, resource constraints, and a pre-specified deadline in its formulation;
- The model considers the impact of both weather conditions and different productivity factors;
- The model considers the variation of work amount among sites;

It should be noted that the model is still far from ideal, and research is still needed to address several practical issues. Among the ongoing improvements is enhancing the model to consider the optimum site order for each individual activity, improving the visual representation of the schedule, and considering actual progress events in the schedule optimization. Full coding of all scheduling options into the CP language is still an ongoing work.

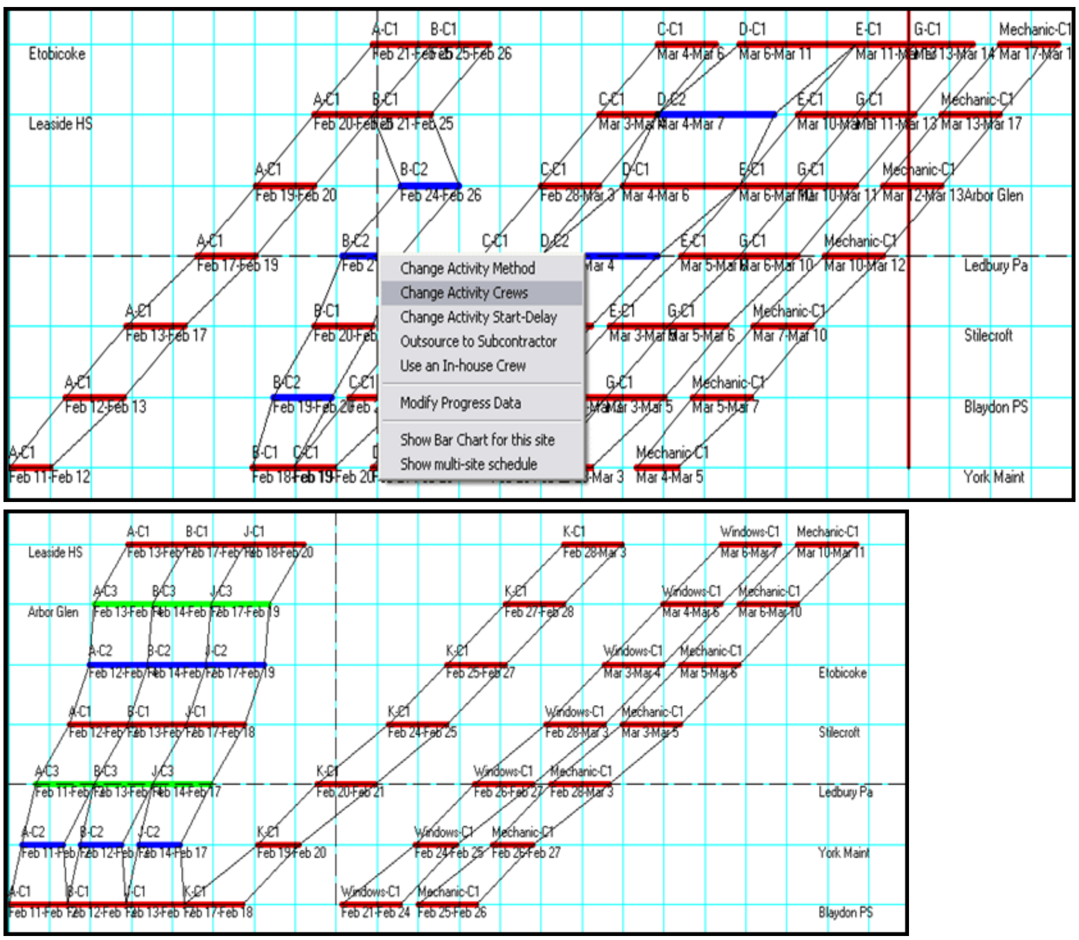


Figure 6: Schedule before and after Optimization

4 CONCLUSION

This paper presented a model to schedule and optimize the delivery phase for scattered repetitive M/R projects. The full model development is currently on going and represents a substantial task due to large coding effort needed. The model's objective is to minimize total construction cost (i.e., direct cost, indirect cost, penalties, and incentives) while meeting project constraints. The model targets to determine the optimum construction method, number of crews, optimum site order, and the proper crew assignment strategies to meet specific deadline while maintaining the work continuity and crew synchronization. The model uses the constraint programming (CP) technique that is capable of handling large-scale problems. The proposed model has the potential to provide large public organizations such as municipalities, universities, and school boards with an effective scheduling tool that is particularly designed to address the challenges facing their management teams in delivering large and scattered infrastructure M/R programs.

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