Proceedings of the 2021 Winter Simulation Conference
S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo and M. Loper, eds.

ENHANCED RESOURCE SCHEDULING FRAMEWORK FOR INDUSTRIAL CONSTRUCTION PROJECTS

Maedeh Taghaddos
Yasser Mohamed
Simaan AbouRizk

Department of Civil and Environmental Engineering
University of Alberta
5-080 Natural Resources Engineering Facility
Edmonton, AB T6G 2W2, CANADA

Hosein Taghaddos

School of Civil Engineering
College of Engineering
University of Tehran
Tehran, IRAN

Ulrich (Rick) Hermann
PCL Industrial Management Inc.
5402 99 St. NW
Edmonton, AB T6E 3P4, CANADA

ABSTRACT

The time and cost required to optimize resource assignments in industrial construction is exacerbated by the size, complexity, and specialized requirements of these projects. This study introduces an automated, simulation-based scheduling method to enhance, accelerate, and facilitate variable resource allocation in industrial construction. The proposed framework links a time-stepped simulation engine to an integrated database management system containing project information and historical data. The developed system auto-generates an efficient schedule respecting project constraints and uncertainties, such as limited resource availability and variable labor resources based on historical data, calendars, and shifts. Graph theory algorithms are used to optimize variable resource allocation in the time-stepped simulation, resulting in the leveling of resource histograms and, consequently, the generation of an efficient project schedule. Applying the proposed framework to an illustrative example demonstrated its capabilities in generating efficient schedules based on variable resource allocation constraints.

1 INTRODUCTION

Effective resource allocation plays a crucial role in large-scale construction projects. Characterized by a relatively large number of tasks and field crews, efficient resource allocation is especially vital in industrial construction. Optimizing resource assignments during the planning phase of these projects can enhance project success by increasing resource utilization, reducing project delays, and decreasing project costs.

Recognizing the difficulty with scheduling projects of this type and size, the Construction Owners Association of Alberta (COAA) promoted WorkFace Planning (WFP) as a best practice for scheduling mega industrial projects in 2005 (CII 2013; COAA 2013; Ryan 2009). WFP involves the development of Field Installation Work Packages (FIWP). These work packages are designed to have a limited, manageable scope (e.g., 1000 to 2000 labor-hours performed in 1- or 2-week intervals) and contain drawings and information needed for field crews to perform the work (Ryan 2009). The WFP structure provides practitioners with the foundation required to enhance scheduling while considering various project constraints.

978-1-6654-3311-2/21/$31.00 ©2021 IEEE

However, many industrial construction projects are performed using a fast-track approach, where detailed design information is released throughout the construction phase. As such, project planning and resource allocation at the beginning of a project must be carried out using limited engineering information (approximately 30-40% available at this stage). Due to the lack of information required to derive WFP-based schedules, preliminary schedules for fast-track industrial projects are typically developed at a high level and are redeveloped once detailed engineering information becomes available (i.e., 6-8 weeks before construction). As high-level discipline-based tasks are often long in duration, practitioners cannot optimize variable resource allocation over the project's entirety, thereby limiting potential gains.

Recently, a novel method for generating near-optimized, WFP-compatible schedules using historical project information and expert input was developed (Taghaddos et al. 2021). Although this method can generate near-optimized schedules, the method is based on constant resource allocation and cannot optimize variable resource assignments over a task's duration. Enabling variable resource allocation for long-duration tasks can improve resource allocation strategies by allowing project managers to re-allocate resources over the duration of various tasks to complete high-priority tasks on time. This is in contrast to traditional scheduling platforms, which do not support such variable-resource allocation behaviors.

To overcome this limitation, the present study has developed an automated, simulation-based method to simplify and accelerate variable resource allocation in industrial construction projects. This approach capitalizes on historical information to identify potential resource allocation options for scheduling and optimization purposes. Using historical information to identify potential options allows many project aspects to be intuitively and automatically considered since projects share many similarities. Moreover, this innovative approach allows WFP-compatible schedules and resource histograms to be generated without the need to manually input thousands of project activities and the relationships between them—as is required when using most WFP-based software (Hu et al. 2018).

2 LITERATURE REVIEW

2.1 Scheduling Problems in Construction

The Critical Path Method (CPM), developed by Kelley and Walker (1959), generates project schedules based on assumptions that resources are unlimited, durations are fixed, and the labor effort available for completing activities is constant and certain. Because of this, practitioners often struggle to create efficient schedules that achieve project milestones when resources are limited.

The Resource-Constrained Project Scheduling Problem (RCPSP) attempts to address limited resource availability by prioritizing activities and modifying their sequence within their floats to identify the schedule resulting in the shortest project duration. Although prioritization is performed in consideration of resource availability (Kolisch and Hartmann 1999; Lu et al. 2008), altering the sequence of activities may not be possible in situations where resources are overly limited. As such, the problem must be approached through the assessment of resource increments. Various mathematical, heuristic, metaheuristic, and simulation-based approaches—or a combination thereof—have been developed to solve the RCPSP. Combined computer simulation and meta-heuristic approaches have been used to successfully solve large RCPSP problems that characterize many industrial construction projects (Taghaddos et al. 2021).

2.2 Multi-Mode Resource-Constrained Project Scheduling Problem

The Multi-Mode Resource-Constrained Project Scheduling Problem (MRCPSP) assumes that activities have alternative modes of operation due to uncertain resource allocation. MRCPSP assumes that activity durations (measured in labor hours) differ between assignment options (Menesi and Hegazy 2014). Here, options (i.e., duration modes) are evaluated to identify the schedule with the shortest duration or best resource histogram. A large body of literature has explored methods for solving MRCPSP. MRCPSP problems for small projects have been solved using exact mathematical methods (Baradaran et al. 2012; Jarboui et al. 2008; Menesi and Hegazy 2014). While heuristic and metaheuristic approaches have been used to find near-optimum solutions for larger projects, these approaches fail to provide efficient resource assignment solutions capable of respecting space-sharing conflicts in large-scale industrial projects (Taghaddos et al. 2021; Menesi and Hegazy 2014).

2.3 Application of Multi-Agent Resource Allocation in Complex Problems

Multi-Agent Resource Allocation (MARA) has also been used for resource assignment (Confessore et al. 2007; Liu and Mohamed 2008). MARA's objective is to maximize social welfare within complex and change-prone societies, such as construction, public transportation, and logistics, that are confined to resource allocation (Liu and Mohamed 2008). Here, agents are defined as autonomous decision-making entities (Bonabeau 2002). Although descriptions differ, there is a consensus of agent autonomy in the literature (Weiss 1999). A system of several autonomous agents collaborating in their environment is known as a Multi-Agent System (MAS) (Shoham and Leyton-Brown 2008; Nwana and Ndumu 1999). MARA is a resource allocation structure in MAS. In the MARA language, agents are entities that are bidding for resources (Liu 2009). In the MARA structure, bidding is used in the competition environment to determine the ideal resource allocation. The primary objective of MARA, therefore, is to determine the best resource allocation strategy when multiple options exist.

Similarly, in the bidding language, agents are bidders that are willing to bid on various resource alternatives (Liu and Mohamed 2008; Taghaddos 2010). Different resource allocation techniques can be used in the MARA framework to determine the optimal resource allocation system. In a centralized resource allocation or auction protocol, one component (i.e., an auctioneer) determines the allocation of resources between agents (Buisman et al. 2007; Taghaddos 2010).

There are three different types of auction protocols. The first, a single-good auction, involves selling one good to one agent (i.e., winning bidder). The second, a multi-unit auction, involves selling multiple, identical goods to one or more agents (i.e., winning bidders). Finally, a combinatorial auction involves different units of various goods available to be traded between agents (Shoham and Leyton-Brown 2008). The auction algorithm prescribes that (1) agents submit their bids and (2) the auctioneer then determines the winner based on maximizing social welfare or minimizing total cost by solving the Winner Determination Problem (WDP). Hence, WDP, which is a subset of MARA, determines the ideal allocation of resources between tasks (or resource level for each task).

WDP can be an assignment problem or a scheduling problem. Notably, the scheduling problem is a resource assignment problem, where agents bid for resources over time. As such, the scheduling problem is considered more complex. Researchers have attempted to solve the WDP with various optimization techniques. Wang et al. proposed an expressive bidding language algorithm designed for decentralized scheduling using a depth-first branch and bound search (Wang et al. 2007). Other scholars have applied a greedy algorithm (Taghaddos 2010) or meta-heuristic approaches, such as the genetic algorithm (Raschip and Luchian 2010). The scheduling problem is an NP-hard problem and does not always converge to the global optimum.

Graphs can represent many practical or abstract problems, such as city layouts, transportation routes, or computer data. Graph-based theories are a popular field in mathematics that facilitate the optimization of problems represented by trees. Several methods and algorithms have been introduced to provide solutions to these problems (Evans 2019, Respondek 2016). Despite various applications, graph theory has yet to be applied to address resource allocation problems.

In 2012, Taghaddos and colleagues proposed a Simulation-Based Auction Protocol (SBAP), which integrates MARA and simulation for large-scale resource scheduling problems (Taghaddos et al. 2012). In the SBAP, auctions are periodically held for each resource competition. Agents that are willing to bid in the specified time window (ΔT; e.g., week/month) are identified. Then, by solving the WDP, the auctioneer identifies the resource assignment that maximizes social welfare (or minimizes total cost). The simulation engine then advances the time to the next auction ($t_{(i+1)}=t_{i+dt}$). At the subsequent auction, all activities within the associated time window ($t_i<t<t_{i+\Delta T}$) bid for their required resource. The SBAP framework has been

successfully applied to multiple project environments in industrial modular construction (Taghaddos et al. 2014) and in heavy-lift planning (Taghaddos et al. 2019) to reduce project time and costs.

While SBAP holds promise for addressing resource allocation challenges, the current structure must be modified to accommodate the planning constraints characteristic of fast-track industrial construction. Specifically, SBAP is based on one simulation iteration combined with heuristic methods. Although SBAP works properly for large-scale construction problems, it does not necessarily reach the global optimum solution.

2.4 Research Objective

Many attempts to enhance resource allocation in construction have been reported. However, an approach capable of considering project constraints in the absence of detailed information—particularly for large-scale projects—has yet to be proposed. The development of an integrated framework that can be used in the early planning stage and in the absence of detailed information can bridge this research gap and provide notable benefits to the industry. Such benefits include the generation of near-optimal resource allocations in the early stages of project planning to (1) enhance bid preparation and/or (2) maximize potential efficiency gains. To achieve this research objective, a modified SBAP approach integrated with the optimization engine of a graph-based algorithm is proposed.

3 PROPOSED METHODOLOGY

The proposed framework employs a hybrid, time-stepped simulation operation and optimization engine to generate a high-level schedule with resource allocation and leveling. The developed engine is linked to an integrated database that is populated by practitioners with historical information and the in-use project calendar, milestones, current progress, and trade availability. Once the input data are populated, the hybrid engine allocates resources to reduce schedule duration and flatten the corresponding resource histogram (Figure 1). Specifically, graph theory algorithms are used to automate and optimize resource allocation in consideration of resource ramp-up, task floats, and other project constraints to provide a dependable schedule baseline. Because the schedule is built using a WFP-compliant structure, detailed engineering information is easily integrated as detailed input data become available. Notably, since the framework is linked to an integrated database management system containing project information and historical information, users do not need to possess simulation or optimization knowledge to use the framework in practice. Components of the proposed framework are illustrated in Figure 1 and are detailed as follows.

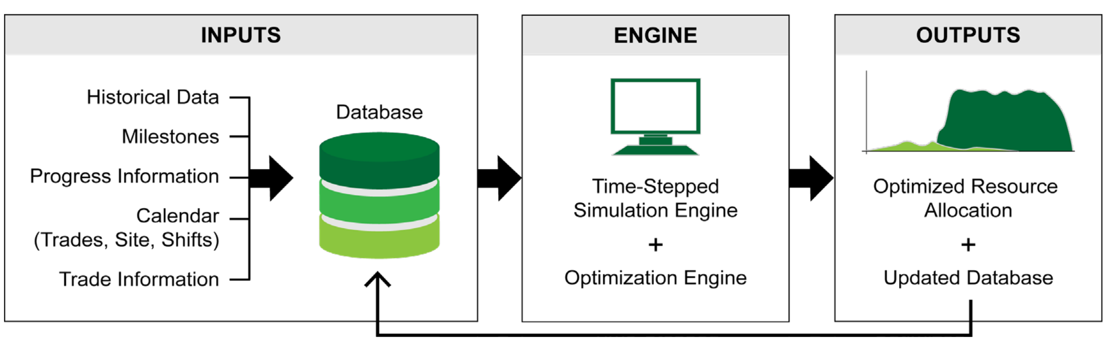

Figure 1. Proposed research framework.

3.1 Inputs

Required inputs for the proposed framework are:

- *Trade Information:* The maximum time-dependent threshold available (e.g., 100 pipefitters available from September to December 2021) and the ramp-up rates for each trade are required.

Trades not requiring leveling by the primary contractor, such as subcontracted trades, must also be identified.

- *Calendar:* A working calendar for each trade is required, which may vary throughout the project's lifecycle. While the project may have a primary calendar, certain trades' calendars may differ and must also be noted.
- *Project Information:* General project information is required, including project start time, worksite capacity (if limited), and the primary project calendar.
- *Historical Data:* S-curve data points for each task, based on the type of work performed, are also required. Details of this are described as follows.

The historical data of previous projects are used to generate s-curves for each task based on the type of work performed (e.g., medium-sized piperack installation). As illustrated in Figure 2, task durations vary, and minimum and maximum values can be determined based on the number of allocated resources. This method uses the boundaries of these historical s-curves as inputs to replace detailed engineering information. First, similar tasks—from the perspective of work-quantity and discipline (e.g., piping for medium piperack)—are identified, and s-curves, similar to those illustrated in Figure 2, are extracted. S-curves for each task are grouped. Each week's minimum and maximum resource allocations are then determined and used to construct minimum and maximum s-curve boundaries. In other words, the minimum boundary s-curve is the minimum of all of the weekly resource allocation s-curves, and the maximum boundary s-curve is the maximum of all of the weekly resource allocation s-curves. The average s-curve, as shown in Figure 2, is the mean of the minimum and maximum boundary s-curves.

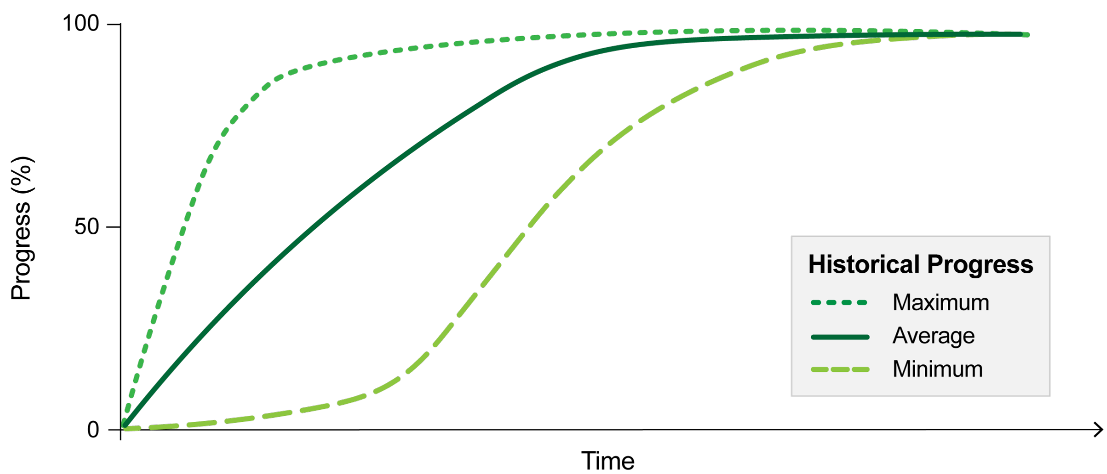

Figure 2. S-curves of task completion (derived from historical data) over time.

3.2 Integrated Simulation and Optimization Engine

To generate the final project schedule with the cited objectives, three consecutive simulation iterations are proposed. The first iteration uses the average resource allocation curves extracted from historical data. Although the result is a variable resource allocation based on historical data, it is essential to note that optimization is not performed in the first iteration. The second and third iterations apply the optimization component to solve the WDP using the generated resource histogram derived in the preceding iterations (i.e., first and second iterations, respectively, are used for the second and third iterations). Each simulation iteration enhances resource leveling by using the results of the preceding interation(s) to more accurately calculate the average resource utilization. In other words, the calculated resource utilization in the current iteration (i.e., run n) is fed into the next iteration (i.e., run n + 1), resulting in a successive reduction of fluctuations and enhancement of utilization.

In this approach, a graph-based algorithm is used as the optimization component. Each iteration is established based on the general concept of the SBAP algorithm from the perspective of time-step advancement and holding consecutive auctions. In this study, a time-stepped simulation is proposed to control the entire system in time-stepped intervals. The protocol is as follows:

1. An auction is held at various time steps for each resource competition.
2. At each auction, agents willing to bid within the specified time window ($t_i<t<t_{i+\Delta T}$ and ΔT; e.g., week/month) are identified.
3. Agents are assessed, and the graph for the agents is constructed.
4. The auctioneer solves the WDP and determines the winners by assessing the entire system (i.e., identifying the path resulting in the minimal total cost).
5. The winners are input into the simulation engine, and the time-step is advanced (i.e., dt) to the subsequent auction ($t_{(i+1)}=t_{i+dt}$).

To solve the variable multi-mode resource allocation problem, two steps are taken. First, tasks are discretized based on a finite period (i.e., time-window duration determined by the practitioner). During this period, the resource allocation remains constant over a discretized task and does not change (Figure 3). Second, in each discretized period, the resource allocation module is employed based on the proposed optimization approach.

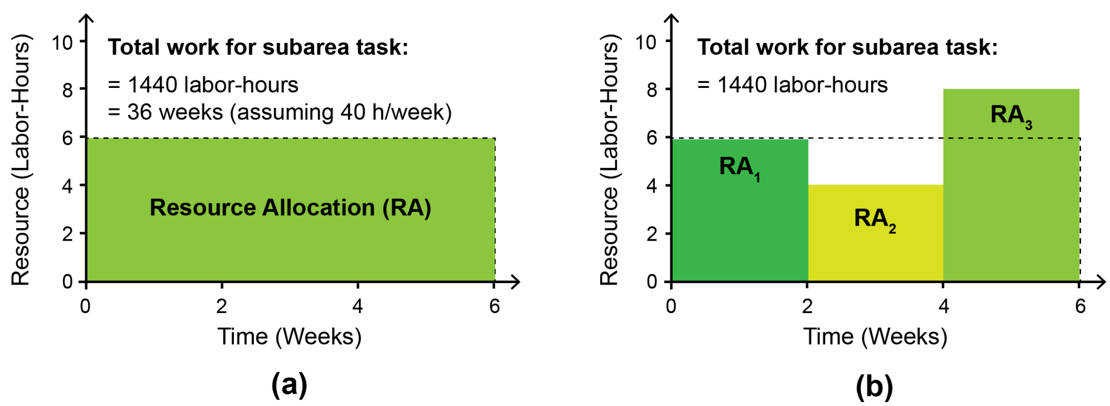

Figure 3. Illustrative example for (a) constant and (b) variable resource allocation over a subarea task.

Once the WDP graph is constructed for each resource competition within a time window, the graph-based optimization is employed to solve the WDP using the deep-first search approach (Cormen et al. 2009). Each agent (i.e., bidder) is a discretized task entity that can only bid for one type of resource in a multi-unit auction, where the type of resource is based on the discipline (e.g., structural steel, pipefitter) associated with the bidders who request the resource. In the constructed graph, each node is associated with one mode (i.e., resource allocation option) of a discretized task based on historical data. To build this graph, eligible tasks for each resource type (i.e., each discipline, such as piping or electrical) are first determined. Then, the tasks are sorted based on the resource's required time (i.e., the absolute time of resource allocation). The structure of the proposed framework is depicted in Figure 4.

The algorithm developed to solve the WDP is detailed in Figure 5. The objective of the consecutive auctions is to identify the winners that minimize the cost of the system. Ideal combinations of cost functions are currently being explored in a separate study. Here, costs are calculated based on the following criteria:

- *Float:* Maintaining task floats above a certain value (e.g., two weeks).
- *Resource Leveling:* Lowering the fluctuations of required resource personnel to limit the hiring and releasing of craft workers.

- *Resource Availability*: Adherence of resource selections to availability constraints, as adding additional resource personnel is costly to the contractor
- *Resource Histogram:* Targeting certain resource histogram shapes (e.g., bell-shape or rectangular histograms) to reduce resource peaks.

The shapes of the resource histograms for each time window are based on two components: (1) in-progress activities, which require resources, and (2) completed activities, which release resources. Information for both must be obtained at each time window, as depicted in Figures 4 and 5.

Time-stepped simulation ensures that the feasibility of the schedule, as well as all logic and relationships, are respected by the simulation engine. In contrast to mathematical methods, there is no need to determine the feasibility of generated schedules. Moreover, the schedules can easily combine with a priority pool for resource allocation prioritization, as it can oversee the queues behind each resource. Such functionality is essential for mimicking a project manager's behavior, such as prioritizing the task with a lower float to capture a limited resource or other combinatory rules based on project objectives (e.g., resource leveling and float). The proposed framework can also regenerate the optimized schedule in response to actual, real-time project data or when the construction schedule deviates from the original schedule.

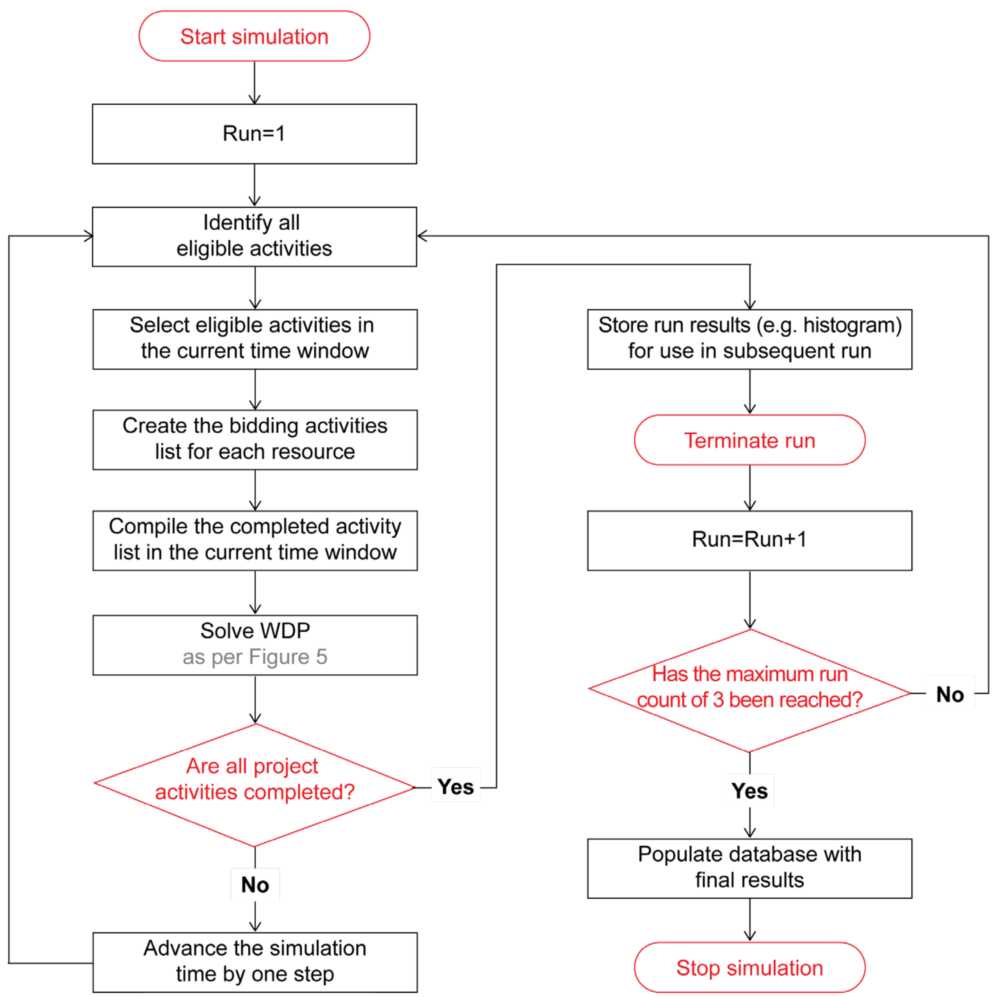

Figure 4. General structure of the proposed framework.

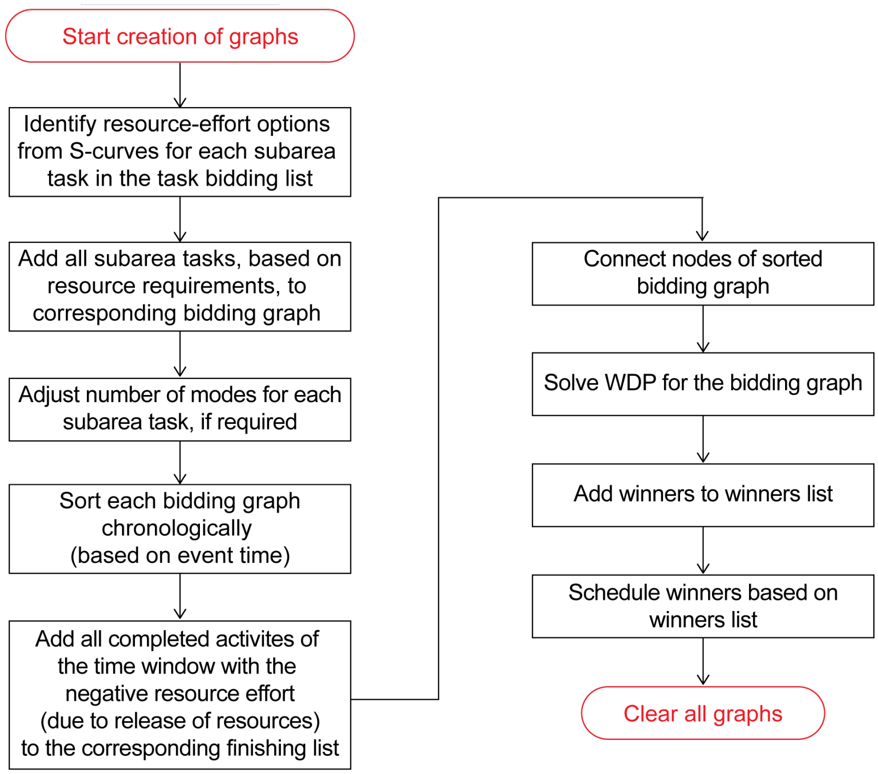

Figure 5. Solving the WDP in the proposed graph-based framework.

3.3 Outputs

Implementation of the framework will enable variable resource allocation (i.e., labor effort for the time window) over a task's duration to be determined. With this output, the resource histogram is automatically generated. Notably, the proposed framework allows the automatic regeneration of an optimized schedule if construction deviates from the original schedule or if project information is changed within the integrated database.

3.4 Testing the Model

The proposed framework was tested using an extreme condition validation test, as described by Sargent (2010). For the first extreme condition, task prioritization criteria were limited only to float, while resources were unlimited. Under these conditions, all resource allocations were selected based on the maximum progress curves, as expected. The other extreme condition introduced too many modes into the system. Instead of the minimum, average, and maximum resource allocation modes, 10 modes were used. As expected, the resulting histogram was much smoother than the histogram obtained using only three modes, demonstrating that the framework behaved as expected.

4 ILLUSTRATIVE EXAMPLE

An illustrative example was used to demonstrate the functionality of the proposed approach. The example project consisted of 13 activities involved in the construction process of a boiler, fin fan, and exchanger. The activities were carried out by multiple disciplines, namely electrical, piping, structural steel, instrumentation, and mechanical. The total labor hours of assigned work, as well as the early start and late finish dates, differed for each discipline. The project calendar was set to 5 working days per week, with 10 working hours per day. Historical data for each discipline were retrieved from existing databases. Simphony

Core Services of Simphony.Net (version 4.6) were used for simulation purposes (AbouRizk et al. 2016), and the Visual Studio 2017 programming environment was used to implement the framework.

Project data, task logic (i.e., predecessor and successor relationships), time-dependent resource availability, and the resulting project schedule were integrated and stored in a database. The associated resource histogram and simulated s-curves were derived and visualized. In this study, a time window and time-step of 50 and 25 working hours were chosen, respectively. The project began on 03/03/2014 and was completed on 05/11/2015. An example of the resource histogram for the electrical discipline is illustrated in Figure 6. Historical and simulated s-curves for a piping task-specific model are shown in Figure 7. Task durations, which were extracted from historical data, ranged from 3 to 70 weeks. The duration predicted by the simulation model was approximately 69 weeks. This duration resulted in the smoothest resource histogram while respecting project constraints. It is important to note that this task has a finish-to-finish relationship with its predecessor, which prevents the task from being completed sooner. Therefore, shortening the task duration may require changing predecessor milestones to allow predecessor tasks to be completed earlier.

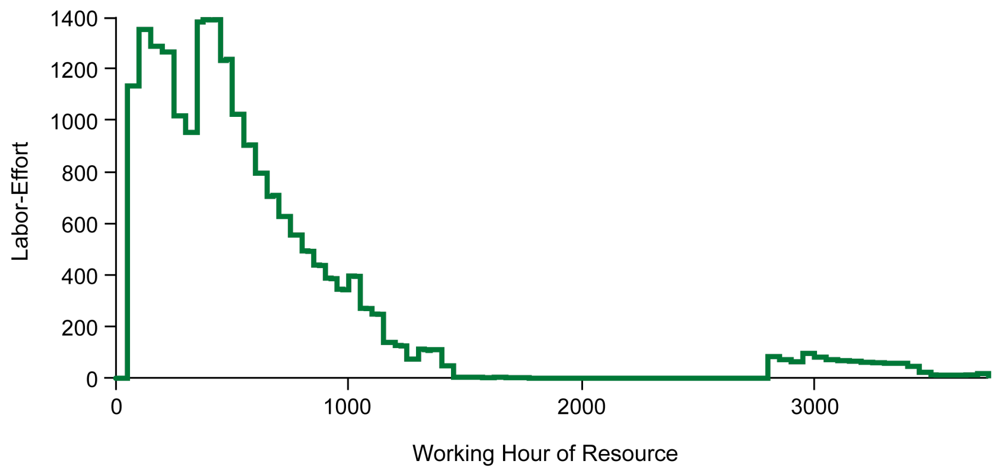

Figure 6. Resource histogram for electrical discipline over the entire project.

As shown in Figure 7, the proposed framework automatically generated a near-optimized resource allocation plan and, consequently, a detailed project schedule. Notably, a non-constant labor effort allocation (i.e., variable slope) was observed due to the tasks' long durations. The variability prescribed by the proposed framework is based on historical data.

A practitioner may consider altering the milestones of specific tasks to smooth the resource histograms further. For example, in Figure 6, modifications may be made to reduce the number of peaks in the histogram to one (i.e., remove peak at approximately 3000 working hours). Moreover, the schedule generated by the framework mimics the resource allocation concerns of project managers during prioritization. For example, tasks with lower floats have a higher priority for capturing limited resources.

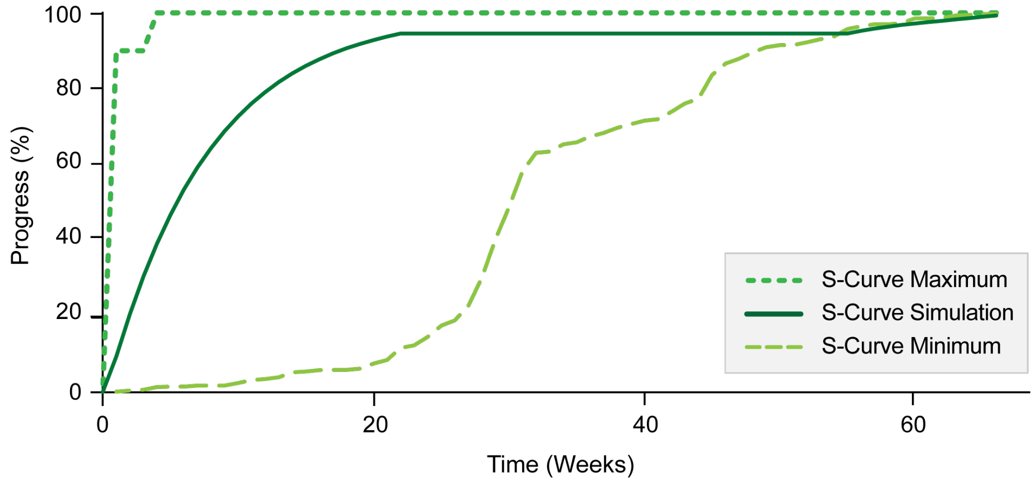

Figure 7. Simulation curve of a task versus minimum and maximum s-curves of historical data.

5 CONCLUSIONS

This paper proposes a novel, hybrid, time-stepped simulation and optimization method for industrial projects to capture early planning uncertainties using historical data. The novel approach uses graph-based optimization integrated with time-stepped simulation to solve resource allocation problems in complex industrial projects when detailed information is lacking. Notably, the proposed framework considers variable resource allocation to provide flexibility in the schedule.

The method's ability to automatically level resource histograms and generate efficient project schedules was demonstrated through an illustrative example. The feature of linking with an integrated database facilitates the practical application of the framework. End users are no longer required to redevelop the simulation or optimization models in response to changing project conditions, reducing the time and knowledge required to use the application. Notably, the schedule created by the proposed framework is compliant with WFP principles, thereby reducing the effort required to generate WFP-based schedules as detailed engineering information becomes available.

Future work can expand the algorithm to consider space and congestion constraints and minimize crew relocation on large industrial sites. The functionality of the proposed approach should be evaluated following its application to a real industrial case study. It is important to note that the proposed approach is not appropriate for optimizing resource allocation at the detailed work-package level. Instead, its application is best suited for higher scheduling levels (e.g., discipline-level between levels 3 and 5).

ACKNOWLEDGMENTS

This research is sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC) through a Collaborative Research and Development Grant (CRDPJ 492657). The authors would also like to acknowledge PCL Industrial Management Inc. for their in-depth knowledge and support.

REFERENCES

AbouRizk, S., S, Hague., R, Ekyalimpa., and S, Newstead. 2016. "Simphony: A Next Generation Simulation Modelling Environment for the Construction Domain". *Journal of Simulation* 10(3):207-215.

Baradaran, S., S.F. Ghomi, M. Ranjbar, and S.S. Hashemin. 2012. "Multi-Mode Renewable Resource-Constrained Allocation in PERT Networks". *Applied Soft Computing* 12:82–90.

Bonabeau, E. 2002. "Agent-Based Modeling: Methods and Techniques for Simulating Human Systems". *Proceedings of the National Academy of Sciences* 99(3):7280-7287.

Buisman, H., G. Kruitbosch., and N. Peek. 2007. "Simulation in Multiagent Resource Allocation". In *Proceedings of the 1st NSVKI Student Conference*, edited by T. Goosen, J. Janssen, 1-6. Utrecht, Netherlands: Utrecht University.

Confessore, G., S, Giordani., and S, Rismondo. 2007. "A Market-Based Multi-Agent System Model for Decentralized Multi-Project Scheduling." *Annals of Operations Research* 150(1):115-135.

CII. 2013. "Advanced Work Packaging: Implementation Guidance". Report No. IR272-2, Version 3.1, Construction Industry Institute, Austin, Texas.

COAA. 2013. COAA Workface Planning Rules. Construction Owners Association of Alberta, Edmonton, Canada. https://www.coaa.ab.ca/library/page/56//, accessed 27th March, 2021.

Cormen, T.H., C.E, Leiserson., R.L, Rivest. and C, Stein. 2009. *Introduction to Algorithms.* 3rd ed. Cambridge, Massachusetts: MIT Press.

Evans, J. 2017. *Optimization Algorithms for Networks and Graphs*. Boca Raton, Florida: CRC Press.

Hu, D., Y. Mohamed, H. Taghaddos, and U. Hermann. 2018. "A Simulation-Based Method for Effective Workface Planning of Industrial Construction Projects". *Construction Management and Economics* 36:328–347.

Jarboui, B., N. Damak, P. Siarry, and A. Rebai. 2008. "A Combinatorial Particle Swarm Optimization for Solving Multi-Mode Resource-Constrained Project Scheduling Problems". *Applied Mathematics and Computation* 195:299–308.

Kelley Jr., J. E., and M. R. Walker. 1959. "Critical-Path Planning and Scheduling". In *Papers Presented at the December 1-3, 1959, Eastern Joint IRE-AIEE-ACM Computer Conference*, 160-173. New York, NY: Association for Computing Machinery.

Kolisch, R., and S. Hartmann. 1999. "Heuristic Algorithms for the Resource-Constrained Project Scheduling Problem: Classification and Computational Analysis". In *Project Scheduling*, edited by J. Węglarz, 147–178. Boston, Massachusetts: Springer.

Liu, Y., and Y. Mohamed. 2008. "Multi-Agent Resource Allocation (MARA) for Modeling Construction Processes". In *Proceedings of the 2008 Winter Simulation Conference*, edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, and J. W. Fowler, 2361-2369. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Liu, Y. 2009. *Modeling Industrial Construction Processes Using Multi Agent Resource Allocation Framework*. M.Sc. thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada. https://www.bac-lac.gc.ca/eng/services/theses/Pages/item.aspx?idNumber=729988869, accessed 28th March 2021.

Lu, M., H. Lam, and F. Dai. 2008. "Resource-Constrained Critical Path Analysis Based on Discrete Event Simulation and Particle Swarm Optimization". *Automation in Construction* 17:670–681.

Menesi, W., and T. Hegazy. 2014. "Multimode Resource-Constrained Scheduling and Leveling for Practical-Size Projects". *Journal of Management in Engineering* 31:04014092.

Nwana, H. S., and D.T, Ndumu. 1999. "A Perspective on Software Agents Research". *The Knowledge Engineering Review* 14(2): 125-142.

Raschip, M. and H. Luchian. 2010. "Using Messy Genetic Algorithms for Solving the Winner Determination Problem". In *Proceedings of the 12th Annual Conference Companion on Genetic and Evolutionary Computation*, edited by M. Pelkian, 1825-1832. New York, NY: Association for Computing Machinery.

Ryan, G. 2009. *Schedule for Sale: Workface Planning for Construction Projects*. Bloomington, Indiana: AuthorHouse.

Respondek J.S. 2016. "Incremental Numerical Recipes for the High Efficient Inversion of the Confluent Vandermonde Matrices". *Computers and Mathematics with Applications* 71(2):489-502.

Shoham, Y., and K. Leyton-Brown. 2008. *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*. Cambridge, United Kingdom: Cambridge University Press.

Sargent, R.G. 2010. "Verification and Validation of Simulation Models". In *Proceedings of the 2010 Winter Simulation Conference*, edited by B. Johansson, S. Jain, J. R. Montoya-Torres, J. Hugan, and E. Yücesan, 166-183. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Taghaddos, H., A. Eslami, U. Hermann, S. AbouRizk, and Y. Mohamed. 2019. "Auction-Based Simulation for Industrial Crane Operations". *Automation in Construction* 104:107–19.

Taghaddos, H. 2010. *Developing a Generic Resource Allocation Framework for Construction Simulation*. PhD thesis., Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, https://doi.org/10.7939/R3T671.

Taghaddos, H., S. AbouRizk, Y. Mohamed, and U. Hermann. 2012. "Simulation-Based Auction Protocol for Resource Scheduling Problems". *Journal of Construction Engineering and Management* 138(1):31–42.

Taghaddos, H., U, Hermann., S, AbouRizk., and Y. Mohamed. 2014. "Simulation-Based Multiagent Approach for Scheduling Modular Construction". *Journal of Computing in Civil Engineering* 28(2):263–274.

Taghaddos, M., H. Taghaddos., U. Hermann., Y. Mohamed., and S. AbouRizk. 2021. "Hybrid Multi-Mode Simulation and Optimization for Subarea Scheduling in Heavy Industrial Construction". *Automation in Construction* 125:103616.

Wang, C., H. Ghenniwa., and W. Shen. 2007. "A Winner Determination Algorithm for Auction-Based Decentralized Scheduling". In *Proceedings of the 6th International Joint Conference on Autonomous Agents and Multiagent Systems*, Article 101, 1-8. New York, NY: Association for Computing Machinery.

Weiss, G. 1999. *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*. Cambridge, Massachusetts: MIT Press.

AUTHOR BIOGRAPHIES

MAEDEH TAGHADDOS is a PhD Candidate in the Department of Civil and Environmental Engineering at the University of Alberta. She received both her B.Sc. in Civil Engineering in 2013 and M.Sc. in Construction Engineering and Management in 2015 from the University of Tehran, in Tehran, Iran. Her research interests include scheduling, discrete-event and time-stepped simulation, and optimization. She is currently working on scheduling improvements for large-scale construction projects, with a focus on the industrial sector. Her email address is taghaddo@ualberta.ca.

HOSEIN TAGHADDOS is an Assistant Professor in the School of Civil Engineering at the University of Tehran. He earned his Ph.D. in Construction Engineering and Management from the University of Alberta. He is currently the director of the Tecnosa R&D Center at the University of Tehran. He is also the director of Smart Plan Solutions, a company in Alberta, Canada. His research interests include Building Information Modeling (BIM), simulation modeling, machine learning, Artificial Intelligence (AI), and their application in the CEM domain. His email address is htaghaddos@ut.ac.ir. His website is https://tecnosa.ut.ac.ir/.

YASSER MOHAMED is a Professor in the Department of Civil and Environmental Engineering at the University of Alberta. His research interests include discrete-event simulation, distributed simulation, data mining, and machine learning, as well as their application in the construction engineering and management domain—particularly in the areas of off-site operations and modular and industrial construction projects. His email address is yaly@ualberta.ca.

ULRICH (RICK) HERMANN is Manager of Construction Engineering at PCL Industrial Management Inc. He is responsible for a broad range of technical support, including engineered lift studies, lift procedures, rigging equipment, and special construction designs, historical data collection and analysis, and major project scheduling setups. Rick graduated from the University of Alberta in 1985 with a Civil Engineering Degree and has since worked in the construction industry for 36 years. His experience is primarily in the industrial sector, working for both owners and contractors. He has been with PCL Industrial for over 26 years. His email address is RHHermann@pcl.com.

SIMAAN ABOURIZK is a Distinguished University Professor, Interim Dean of the Faculty of Engineering at the University of Alberta, and a Tier 1 Canada Research Chair in Operations Simulation. For almost 30 years, Dr. AbouRizk and his research team have focused on advancing simulation modeling for improved management and control of large-scale construction projects. His work has resulted in several long-standing industrial research partnerships and in the development of numerous simulation tools that have been implemented throughout the construction sector. Partnering with 40 construction organizations, the success and distinctiveness of Dr. AbouRizk's research program are a consequence of building strong industrial research partnerships focused on advancing research, teaching, and overall practice. His email address is abourizk@ualberta.ca.