Joint CSCE Construction Specialty & CRC Conference 2025
Conférence conjointe spécialisée en construction de la SCGC et CRC-2025

Montreal, Quebec
July 28-31, 2025 / *28-31 juillet 2025*

Optimum Crew Scheduling and Visualization for Scattered Repetitive Projects Using ARCGIS

Saeed, F.[1,2,3*] and Hegazy, T.[1,4]
[1] Dept of Civil & Environmental Engineering, University of Waterloo, Waterloo, ON, Canada
[2] Dept of Civil Engineering, Aswan University, Aswan, AS, Egypt
[3] ffasaeed@uwaterloo.ca; fam.fahmy@aswu.edu.eg
[4] tarek@uwaterloo.ca

ABSTRACT: Planning the delivery of Scattered Repetitive Projects (SRPs), such as multi-school rehabilitations, is a challenging task to determine the work sequence for the crews to meet delivery constraints. Traditional scheduling methods struggle to handle the unique challenges posed by geographically dispersed work units, where crew travel times, work conditions, and site-specific constraints are pivotal factors to project success. ARCGIS, as one of the Geographic Information Systems (GIS) technology, offers a promising approach for optimizing crew routing by addressing these spatially dependent challenges. This study, therefore, investigates the applicability and adaptability of ARCGIS's Vehicle Routing Problem (VRP) tool which applies to a single routing task to the more general problem of scheduling SRPs that involve multiple construction tasks over a period of time. ARCGIS provides substantial support by enabling real-time traffic updates, which affect crew routing decisions. ARCGIS was therefore implemented to model optimal routing of multiple crews among various scattered sites to minimize the overall travel time of the crews. Additionally, spatial data is utilized to address site-specific constraints like access limitations and work hours. Some adaptation was also done to offset the ARCGIS inability to consider advanced scheduling needs such as varying productivity rates and considering crew fatigue/learning effects, which are essential for SRPs. Overall, the paper highlights various ARCGIS adaptations to incorporate dynamic productivity rates, handle multi-tasks with relationships; and efficiently manage consumable resources. The paper also discusses the potential of using a hybrid approach combining ARCGIS with an optimization algorithm to enhance the scheduling efficiency of SRPs, making this a viable strategy for the multi-billion-dollar industry of infrastructure rehabilitation.

1. INTRODUCTION

The construction industry, one of the largest contributors to the economical growth of any country, is currently facing serious challenges in terms of project delays, cost overruns and labour shortage (Sixth Annual Report - CRUX Insights 2023). Literature shows that between 25% and 50% of large construction and maintenance projects experience delays and cost overruns (Saeed et al. 2024a; Siemiatycki 2015). Scattered Repetitive Projects (SRPs), such as the rehabilitation of multiple schools, bridges, or housing units, represent a significant segment of the construction industry. These projects involve tasks that are repetitive in nature across multiple geographically dispersed units. Thus, repetitive scheduling techniques can bring multiple benefits, including economy of scale and learning curve savings. However, the scattered nature of these projects poses more logistical and scheduling challenges due to the need to coordinate crew movements, optimize travel times, and adapt to diverse site-specific constraints. Therefore, such benefits can only be achieved under optimal allocation of the working crews among the repetitive units, allowing the crews to work continuously without interruption (Hegazy and Kamarah 2022; Saeed et al. 2024b). Such optimal allocation of crews, however, is not a simple task and yet traditional scheduling methods often fall short in addressing the inherent spatial complexity of SRPs.

Unlike the classic shortest project duration problem in project management, which focuses on determining the minimum time required to complete a set of interdependent activities within a single, centralized project network, SRPs extend this challenge across multiple, physically dispersed sites. In such cases, each site may require a subset of tasks to be performed under local constraints, while crews must be shared and relocated across the network. Similarly, the shortest path problem (Wu et al. 2023) in transportation engineering typically addresses static routing between two points or among nodes in a network, often disregarding temporal constraints, activity durations, or resource interactions. SRPs, however, demand a multi-layered integration of both temporal scheduling and spatial routing. Crews must not only travel efficiently between sites but also execute sequences of tasks under varying productivity rates, constrained work hours, and potentially conflicting site access rules. This results in a spatial-temporal scheduling problem that couples logistical routing with resource-constrained project scheduling, thus requiring more advanced and adaptable methodologies than those offered by traditional scheduling or routing tools alone.

Geographic Information Systems (GIS) technology has emerged as a promising solution for addressing the spatial challenges of SRPs and their adoption in the construction-related research is expanding rapidly (Akindele et al. 2023). GIS-based tools have proven to be essential in various disciplines including scheduling repetitive construction projects (Tomar and Bansal 2022), modeling the construction supply chain (Uzairuddin and Jaiswal 2022), enhancing the waste collection process (Herrera-Granda et al. 2024), etc. Among the effective GIS tools, ARCGIS Pro software has been widely used, and its most powerful analysis layers is the Vehicle Routing tool which stands out as a robust framework for optimizing the movement of vehicles across scattered locations. VRP tool was developed mainly to solve the well-known vehicle routing problem (VRP), where the VRP solver tries to find the best routes for a fleet of vehicles to service many orders. It enables planners to model optimal routing paths between work units, taking into account factors such as travel distances, traffic conditions, and location-specific constraints (Nguyen and Tran 2024). The process of scheduling SRPs has been proven to share many constraints and characteristics with the VRP, where crews travel across different units to complete their tasks. Such similarities could make the VRP tool a great option for the construction industry to adopt it.

Thus, this study explores the applicability of ARCGIS's VRP analysis layer (tool) for scheduling SRPs and assess its potential to address the unique challenges posed by geographically dispersed projects. The research focuses on how VRP can optimize crew routing and enhance adherence to project deadlines while identifying its limitations in handling dynamic scheduling needs. By minimizing travel time and improving route efficiency, VRP tool has the potential to enhance overall project performance and reduce logistical overhead. The study uses ARCGIS Pro software (version 3.0.0) under the license of the University of Waterloo, Ontario, Canada. A sample SRP was selected as a case study, with its results presented and discussed in the following sections.

2. BACKGROUND

Repetitive projects are usually categorised, based on the geographical characteristics of their units, into three main groups: (1) Scattered Repetitive Projects (e.g., multi-school rehabilitations); (2) Linear Repetitive Projects (e.g., highways and pipelines); and (3) Vertical Repetitive Projects (e.g., high-rise buildings) (Saeed et al. 2024a). All types of repetitive projects share some challenges where the schedule needs to meet variety of constraints (maintaining crew-work continuity, handling limited resources, meeting strict deadline, etc.). However, the scattered nature of the units in the SRPs add another layer of complexity to the scheduling problem. Thus, this study focuses on optimizing the planning and scheduling of SRPs.

Despite the extensive literature efforts on repetitive scheduling generally and on SRPs scheduling specifically over the past two decades, a limited number of studies investigated the use of varying unit orders, which is an additional degree of freedom for SRPs (first column of Table 1). Among existing efforts, Podolski and Sroka (2019) determined a near-optimal execution order among repetitive units in the case of a single task crew with a fixed productivity rate across the units of a task. To avoid this limitation, Hegazy and Kamarah (2022) proposed a comprehensive model to optimize the allocation of multiple crews among non-identical scattered sites while considering crew moving time and cost. The key advantage of Hegazy and Kamarah (2022)'s model, making it a good starting point for the present research, is that the activities use multiple crews and independent execution orders among the units. One limitation is that the model estimates travel times among units roughly by dividing travel distance by a fixed moving speed. Overall, literature shows that only limited studies (e.g., (Arashpour et al. 2017; Gad et al. 2023)) allow multiple activity crews with pre-specified skill sets, however they are fixed among all crews. Furthermore, to the authors knowledge, currently developed models do not consider crews' capacity to handle consumable resources during work or during moving from one unit to another.

On the other side, Geographic Information Systems (GIS) tools have been widely utilized in the construction industry for project planning, route optimization, and logistics management. Han et al. (2022) developed an integrated GIS-BIM model to perform real-time and full-process quality evaluation on asphalt pavement construction. Their model was applied in the Phnom Penh-west Halluk highway construction project, in which the GIS early located and marked the sections with poor construction quality, and the BIM models acquired comprehensive information on the road sections. In another effort, Irizarry et al. (2013) presented an integrated GIS-BIM model to keep track of the supply chain status and provide warning signals to ensure the delivery of materials to construction sites. First, BIM was implemented to accurately provide a detailed takeoff in an early phase of the procurement process. Then, GIS was used to support the wide range of spatial information used in the logistics perspective (warehousing and transportation). Regarding construction project scheduling, Tomar and Bansal (2022) developed an interactive tool for project scheduling in a GIS environment for both repetitive and non-repetitive units. However, the way to quantify and consider the effects of surroundings on the schedule was unclear.

Table 1: Recent models for scheduling scattered repetitive projects (SRPs).

Reference	Order of Execution	Multiple Crews	Different Crew Productivity Rates	Non-identical Units	Unit Priorities	Adopted Model
(Hegazy and Kamarah 2022)	√	√		√		Modified FCFS*
(Podolski and Sroka 2019)	√		√	√		Simulated Annealing
(Huang et al. 2016)				√		Genetic Algorithm
(Monghasemi and Abdallah 2021)	√			√	√	Linear Optimization
(Mostafa et al. 2022)	√	√		√		Enhanced CPM/LOB**
(Gad et al. 2023)		√		√		Agent-based Simulation

*First-Come-First-Served
**Critical Path Method/ Line of Balance

The current study, as part of ongoing research, have conducted an extensive review of the available GIS-based tools with promising capabilities to handle the various constraints of scheduling the SRPs. ARCGIS's VRP analysis layer was chosen as a prominent tool that is gaining increasing attention in the operational research field. VRP is still a relatively new tool, so there is not much published material regarding its application in the field of scheduling construction projects. However, VRP has been applied across different disciplines that already share similar constraints and characteristics as SRPs scheduling process. VRP has been applied to address solid waste collection challenges (Herrera-Granda et al. 2024); optimize truck routing for mixed concrete deliveries to construction sites (Pushpakumara 2021); improve school bus routing efficiency (Eldrandaly and Abdallah 2012); enhance vehicle route optimization for residential recyclables collection (Kůs et al. 2016); streamline food supply chain logistics (Abousaeidi et al. 2016); and maintain the roads serviceability during the snow season (Nguyen and Tran 2024). Furthermore, Das et al. (2024) has used ArcGIS to plan waste collection routes from construction sites to recycling and disposal facilities. The study found that optimized GIS-driven waste collection not only reduced transport costs but also increased the efficiency of waste recycling operations. Thus, VRP tool has been selected for further investigation to assess its applicability to plan and manage the scheduling of SRPs.

3. ARCGIS MODEL

ARCGIS's VRP tool provides unique features through enabling real-time data integration, such as live traffic updates, into the scheduling process which inform routing decisions and enhance flexibility. VRP has proven its ability to model optimal routing paths among work units, minimizing travel time for crews assigned to various scattered sites in different industries. Thus, the proposed framework is designed to use project information (units, durations, constraints, and available resources) to formulate schedule optimization that supports determining the optimum number of crews, methods of construction, as well as the crews' execution orders. The implementation steps of the proposed framework are discussed in the next subsections along with the description of a case study of an example activity in an SRP project.

3.1 Model Description and Case Study Data

The case study used along the description of the proposed model has been adapted from (Saeed et al. 2024b). It encompasses a rehabilitation project of 10 (N) non-identical units that are geographically scattered across different locations (Figure 1). The table in Figure 1 shows the units' location, which is used as the key inputs to the model. Also, the model accepts a user input of the starting points for the 2 (E) crews involved in the activity (i.e., starting point SP) from which a crew starts its move to the assigned work units, and moves back after completing all these tasks. All crews have to start their work from the same starting point (meeting/mobilization point).

ID	Building	Location
1	Building_1	50 Francine Dr., North York
2	Building_2	400 Scarborough Rd., Toronto
3	Building_3	2621 Midland Ave., Scarborough
4	Building_4	29 Lockie Ave., Scarborough
5	Building_5	112 Goldhawk Trial, Scarborough
6	Building_6	1550 Sandhurst Cir, Toronto
7	Building_7	45 Lynmont Rd., Etobicoke
8	Building_8	108 Gladstone Ave., Toronto
9	Building_9	70 Fawcett Trail, Toronto
10	Building_10	1570 Dundas ST. E, Mississauga
SP	Crew Depot	65 Kirkham Dr, Markham
RS	Refill Station	65 Kirkham Dr, Markham

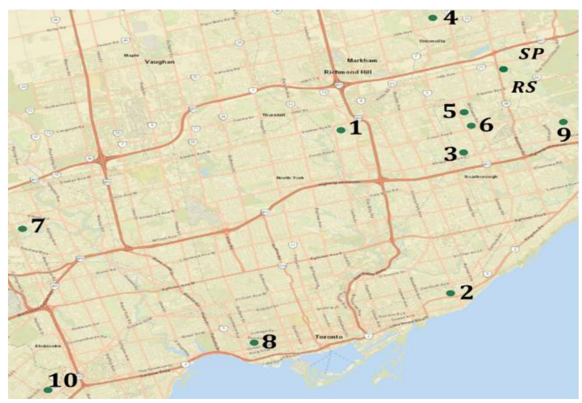
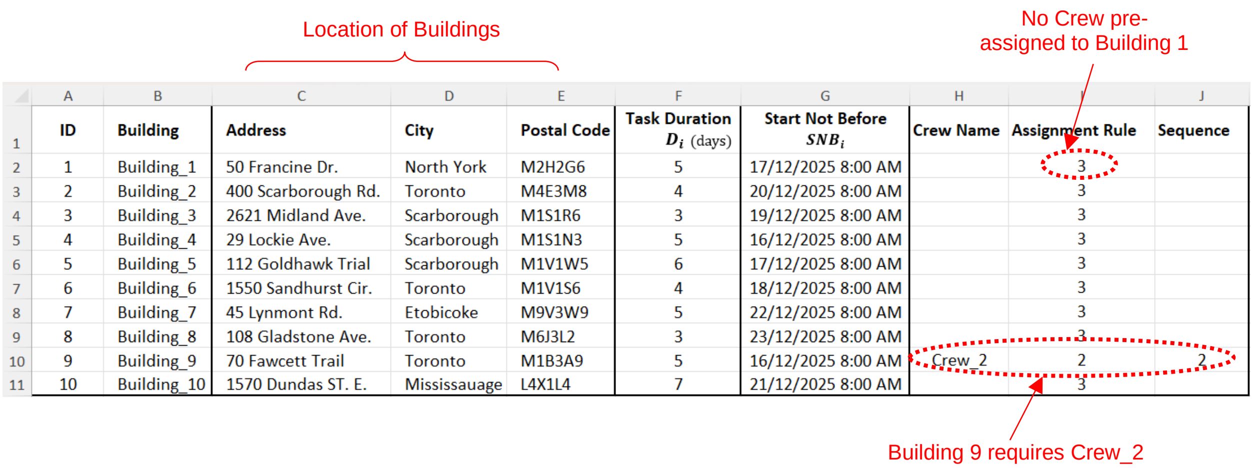


Figure 1: Locations of ten buildings (units), and the crew starting point

The various columns in Figure 2 show the data inputs required for the activity units. Column F shows the time needed to complete the activity (task) in each unit representing the general case of non-identical units. Column G shows the input for the Start-Not-Before (SNB_i) constraint for each unit *i* (date and time) to start the task/project. This constraint means that no work is allowed to start in each unit before the given date and time, representing the expected delivery date of a required material, or receiving any specific approvals (e.g., Environmental, Cultural, Safety, Traffic, etc.). The SNB_i constraint can be also deployed to represent the logical relationships among activities by assigning its value as the finish time of all predecessor activities for this activity.

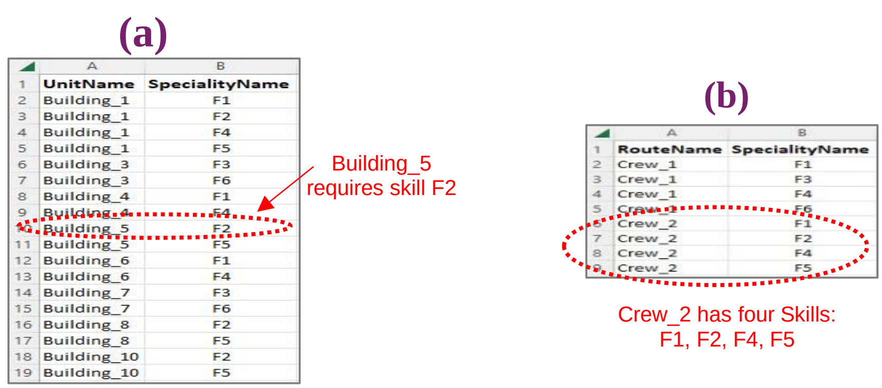


ID	Building	Address	City	Postal Code	Task Duration D_i (days)	Start Not Before SNB_i	Crew Name	Assignment Rule	Sequence
1	Building_1	50 Francine Dr.	North York	M2H2G6	5	17/12/2025 8:00 AM		3	
2	Building_2	400 Scarborough Rd.	Toronto	M4E3M8	4	20/12/2025 8:00 AM		3	
3	Building_3	2621 Midland Ave.	Scarborough	M1S1R6	3	19/12/2025 8:00 AM		3	
4	Building_4	29 Lockie Ave.	Scarborough	M1S1N3	5	16/12/2025 8:00 AM		3	
5	Building_5	112 Goldhawk Trial	Scarborough	M1V1W5	6	17/12/2025 8:00 AM		3	
6	Building_6	1550 Sandhurst Cir.	Toronto	M1V1S6	4	18/12/2025 8:00 AM		3	
7	Building_7	45 Lynmont Rd.	Etobicoke	M9V3W9	5	22/12/2025 8:00 AM		3	
8	Building_8	108 Gladstone Ave.	Toronto	M6J3L2	3	23/12/2025 8:00 AM		3	
9	Building_9	70 Fawcett Trail	Toronto	M1B3A9	5	16/12/2025 8:00 AM	Crew_2	2	2
10	Building_10	1570 Dundas ST. E.	Mississauage	L4X1L4	7	21/12/2025 8:00 AM		3	

Figure 2: Input data for the ten scattered buildings (units) in a sample repetitive activity

As a unique feature of the VRP model, any unit *i* may require non-reusable/consumable resources (e.g., soil for backfill, gravel, reinforcing steel, etc.) and reusable resources (e.g., cranes). For consumable resources, the model can handle up to nine different types of consumable resources to be delivered to the units (e.g., windows), through the Delivery Quantity feature, or to be picked up from the site (e.g., excavated soil), through the Pickup Quantity feature (ESRI 2024). However, these two feature only functionable if the total duration of the project is less than or equal to one day, which is not the case for most of the construction projects. Additionally, any unit *i* may require a specific crew (e.g., having certain unique skill) to complete the work. In this case, the mandatory Crew_ID is listed for those units in column H (e.g., building 9 requires crew 2), and the assignment rule to be set to 2 (Preserve Route) to enforce the assignment of this crew to the unit (ESRI 2024). Also, a valid sequence (2 as shown in Column J in our case) must also be set even though the sequence may or may not be preserved.

The VRP function also has the ability to assign work units with special requirements to crews that meet those specific criteria. To specify the set of required crew skills/features at any units, Figure 3-a specifies the required skills/tools/features, each requirement for a building is inserted in a separate row. These will be used as constraints so that each unit will be assigned the appropriate crew that match the desired feature/skill. Meanwhile, as the model can deal with multiple crews to perform the required work, Figure 3-b shows the data inputs for the two crews involved in the sample activity. Each data row represents an available skill for a crew. These skills will be used to match each unit with crews that best meet their requirements, while optimizing the objective function (e.g., minimizing the overall project duration). The next sub-section goes over the implementation steps of the VRP model to the given case study and display the optimized schedule of the given task.



(a)

UnitName	SpecialityName
Building_1	F1
Building_1	F2
Building_1	F4
Building_1	F5
Building_3	F3
Building_3	F6
Building_4	F1
Building_4	F4
Building_5	F2
Building_5	F5
Building_6	F1
Building_6	F4
Building_7	F3
Building_7	F6
Building_8	F2
Building_8	F5
Building_10	F2
Building_10	F5

(b)

RouteName	SpecialityName
Crew_1	F1
Crew_1	F3
Crew_1	F4
Crew_1	F6
Crew_2	F1
Crew_2	F2
Crew_2	F4
Crew_2	F5

Figure 3: Data input of (a) buildings requirements; and (b) crews characteristics

3.2 Implementation and Results

This study adopts the Vehicle Routing Problem (VRP) analysis layer as part of ARCGIS Pro version 3.0.0 under the license provided through the University of Waterloo. The process begins with case study data preparation. All data were inputted into the software as Excel comma-delimited files (CSV). As shown in Figure 4, this includes defining the locations of units (Orders), the starting and ending points for vehicles (Depots), and preparing a network dataset that represents the transportation infrastructure, such as roads, traffic rules, and travel restrictions. Figure 4-a displays the user interface of the ARC-GIS system with the output routes for the two crews plotted on a map in the middle part, the analysis units (activity time in days, travel distance in kilometers, start date of the project on 8:00 AM, 2025-12-16) in the top part, and the list of the imported datasets representing different input attributes and constraints (discussed in more detail in Figure 4b-d).

Once all the data and parameters are set, the VRP solver is run. The solver processes the inputs and generates optimized routes for the crews, taking into account all constraints, including travel times, site-specific conditions, and capacity limitations, if given. The results include detailed route plans showing the sequence of stops, assigned crews, schedules, and key metrics like total travel time, and distance. After completing the analysis, the VRP solver produced a total duration of 30 days + 2 hours, where Crew 1 served units 4-6-3-7 and Crew 2 served units 9-5-1-2-8-10. Finally, the efficiency of the routes can be assessed, adjustments to be made, if necessary, and the finalized routes and schedules to be exported. These schedules can be shared as maps, reports, or digital files compatible with navigation systems, ensuring the solution is practical and implementable (ESRI 2024).

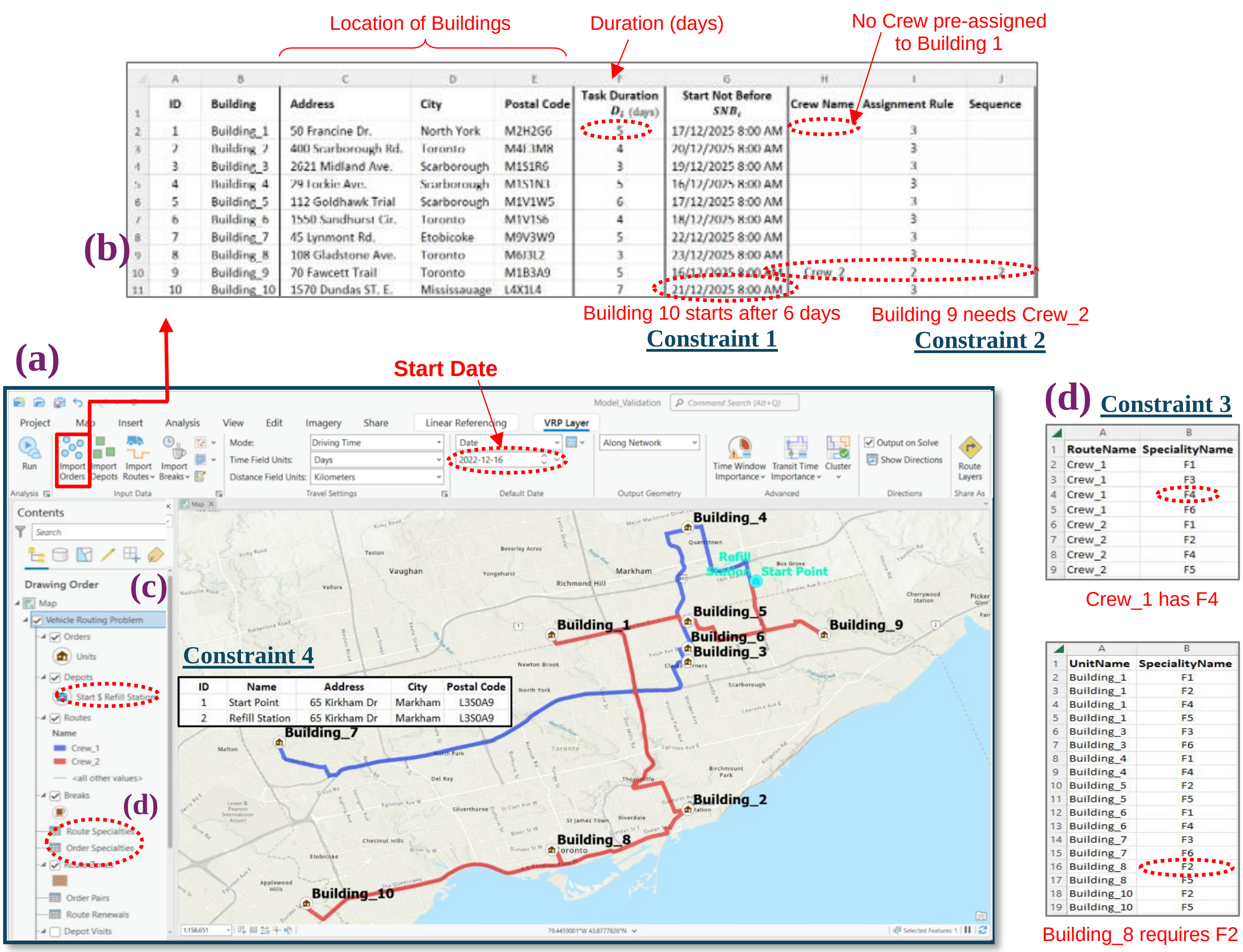


Figure 4: An overview of the ARC-GIS routing.

4. DISCUSSION

The scattered scheduling problem, from an academic perspective, is focusing on developing a scheduling model for SRPs where unit order is key to an optimized schedule. This study takes this academic problem and integrates it with the different practical considerations related to the construction industry such as logistical constraints, crew skills, and site skill requirements**.** Thus, this paper offers the public sector a proven strategy for efficient project delivery, achieving streamlined administrative processes and saving time and money. Furthermore, the case study results proved the promising use of ARCGIS's VRP tool to optimize the schedule of multiple crews among sites that are scattered across a large geographical area through an optimized assignment of crews to tasks. The model has proved its ability to enhance project timelines and reduce the travel time for the crews while considering varying work volumes and crew productivity rates, and live traffic data.

Despite its benefits, the VRP tool still needs to undergo several enhancement and adaptation efforts to be capable of optimizing the high complexities involved in the scattered projects. One effort would be targeting the employed optimization engine. Because the VRP solving engine currently optimizes only one activity at a time, it can be integrated with a CPM/LOB system for repetitive scheduling to support the planning of SRPs. One option is re-designing the repetitive scheduling engine to incorporate all the activities of a project, one at a time, according to the logical relations of the project. In that case, the Start-Not-Before (SNB_i) constraint on each activity will be taken directly from the finish dates of the preceding activities. Alternatively, the model can be used as a powerful routing algorithm for specific activities within the project. On the other hand, the VRP tool has other features yet to be discussed and applied to the scheduling problem of SRPs or other similar disciplines. The VRP tool leverages spatial data to address critical site-specific constraints, such as restricted work hours, unique access conditions, and local environmental factors, all of which are pivotal for meeting project deadlines and maintaining compliance with project requirements. Table 2 provides an overview of the available features in the VRP tool against the key practical constraints identified in the literature for optimizing SRPs schedules.

Table 2: Feature Explanation of the ARCGIS VRP tool

Features Already Used in This Study	
Start & Refill Station	Constraint 4 in Figure 4-a
Multiple Crews	Handles more than one crew working across units
Crew Specialization & Special Units	Constraint 3 in Figure 4-d
Identical and Nonidentical Units	Takes the task duration in unit(s)
Logistical Constraints	Constraint 1 in Figure 4-b
Live Traffic Data	Embedded in the solver engine
Crew Work Sequence	Routes exported as maps/digital file to navigation systems
Features Not Applicable to Construction	
Crew Capacities of Consumable Resources	Only for total project duration <= 1 day
Curb Approach	Direction a vehicle may arrive at and depart from site
Features to be Utilized in the Future	
Restricted work hours	Tasks only allowed during time windows during the day
Unload/Reload Time	Fixed time across all crews
Crew Idle Time	Crew is not working at a unit or travelling between units
Revenue	Weights relative importance of completing the task across units
Objective Function	Total duration, travel time, travel distance
Features Currently Not Available	
Productivity Rates and Duration Calculation	Only one duration input per unit
Crew Fatigue & Learning Rates	Not Applicable
Multiple Tasks	Limited to only one task at a time

To sum up, the VRP is an efficient tool to be utilized to simulate realistic routing scenarios that account for varying site conditions and operational challenges. It is able to incorporate multiple factors, including crew capacities, task durations, and travel constraints, to develop an optimized work sequence for the crews. The integration of these parameters allows the model to generate practical and implementable schedules that align with the objectives of minimizing travel time, enhancing productivity, and adhering to project timelines. However, it still has limitations when it comes to addressing the broader scheduling requirements of SRPs. For instance, it does not account for dynamic crew productivity rates, the impact of fatigue, or the learning curve associated with repetitive tasks. Furthermore, it lacks the capability to produce clear visualization of the schedules which is a critical part to the project managers to get more insights in the project performance. These limitations highlight the need for a more comprehensive approach that combines the spatial optimization strengths of GIS with advanced scheduling and optimization algorithms.

5. CONCLUSIONS

This study investigates the applicability of ArcGIS's VRP tool for optimizing the scheduling of scattered repetitive projects (SRPs). The present study utilizes its powerful capabilities in spatial optimization and real-time routing and proposes improvements to address its limitations in resource management and crew productivity modeling. The findings of this study have important implications for both academia and industry. For researchers, it provides a foundation for further exploration of GIS-based optimization tools/techniques in construction scheduling. For practitioners, it offers insights into how spatial data can be leveraged to improve project planning and execution. By integrating GIS with advanced optimization frameworks, construction managers can leverage the best of both worlds, achieving more efficient, cost-effective, and realistic scheduling for SRPs. Given the growing need for efficient infrastructure rehabilitation and maintenance, the adoption of GIS-based solutions such as VRP will continue to play a vital role in advancing construction project management. By addressing critical gaps in the current planning and scheduling practices for SRPs, this research contributes to the ongoing effort to enhance project delivery in a sector that underpins the functionality and sustainability of modern infrastructure systems.

ACKNOWLEDGMENTS

The work described in this paper was funded by the Ministry of Higher Education of Egypt (Award No. GM – 0407).

REFERENCES

Abousaeidi, M., R. Fauzi, and R. Muhamad. 2016. "Geographic Information System (GIS) modeling approach to determine the fastest delivery routes." *Saudi J Biol Sci*, 23 (5): 555–564. Elsevier. https://doi.org/10.1016/J.SJBS.2015.06.004.

Akindele, O., S. Ajayi, A. S. Oyegoke, H. A. Alaka, and T. Omotayo. 2023. "Application of Geographic Information System (GIS) in construction: a systematic review." *Smart and Sustainable Built Environment*, 14 (1): 210–236. Emerald Publishing. https://doi.org/10.1108/SASBE-01-2023-0016/FULL/XML.

Arashpour, M., R. Wakefield, B. Abbasi, M. Arashpour, and R. Hosseini. 2017. "Optimal process integration architectures in off-site construction: Theorizing the use of multi-skilled resources." *https://doi.org/10.1080/17452007.2017.1302406*, 14 (1–2): 46–59. Taylor & Francis. https://doi.org/10.1080/17452007.2017.1302406.

Das, S., A. Baral, I. M. Rafizul, and S. Berner. 2024. "Efficiency enhancement in waste management through GIS-based route optimization." *Clean Eng Technol*, 21: 100775. Elsevier. https://doi.org/10.1016/J.CLET.2024.100775.

Eldrandaly, K. A., and A. M. F. Abdallah. 2012. "A novel GIS-based decision-making framework for the school bus routing problem." *Geo-spatial Information Science*, 15 (1): 51–59. Routledge. https://doi.org/10.1080/10095020.2012.708151.

ESRI. 2024. "VRP analysis layer - ArcGIS Pro | Documentation." Accessed January 16, 2024. https://pro.arcgis.com/en/pro-app/latest/help/analysis/networks/vehicle-routing-problem-analysis-layer.htm.

Gad, H. Kh., O. Hosny, and N. Khaled. 2023. “Resources-Based Planning Framework for Infrastructure Maintenance and Rehabilitation Projects.” *Computing in Civil Engineering 2023*, 899–907. American Society of Civil Engineers.

Han, C., F. Tang, T. Ma, L. Gu, and Z. Tong. 2022. “Construction quality evaluation of asphalt pavement based on BIM and GIS.” *Autom Constr*, 141: 104398. Elsevier. https://doi.org/10.1016/J.AUTCON.2022.104398.

Hegazy, T., and E. Kamarah. 2022. “Schedule optimization for scattered repetitive projects.” *Autom Constr*, 133: 104042. Elsevier. https://doi.org/10.1016/J.AUTCON.2021.104042.

Herrera-Granda, I. D., J. Cadena-Echeverría, J. C. León-Jácome, E. P. Herrera-Granda, D. Chavez Garcia, and A. Rosales. 2024. “A Heuristic Procedure for Improving the Routing of Urban Waste Collection Vehicles Using ArcGIS.” *Sustainability 2024, Vol. 16, Page 5660*, 16 (13): 5660. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/SU16135660.

Huang, Y., ; Xin Zou, and L. Zhang. 2016. “Genetic Algorithm–Based Method for the Deadline Problem in Repetitive Construction Projects Considering Soft Logic.” *Journal of Management in Engineering*, 32 (4): 04016002. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000426.

Irizarry, J., E. P. Karan, and F. Jalaei. 2013. “Integrating BIM and GIS to improve the visual monitoring of construction supply chain management.” *Autom Constr*, 31: 241–254. Elsevier. https://doi.org/10.1016/J.AUTCON.2012.12.005.

Kůs, K., R. L. Cheu, and T. Horák. 2016. “GIS approach in vehicle route optimization for residential recyclables collection.” *2016 Smart Cities Symposium Prague, SCSP 2016*. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/SCSP.2016.7501024.

Monghasemi, S., and M. Abdallah. 2021. “Linear Optimization Model to Minimize Total Cost of Repetitive Construction Projects and Identify Order of Units.” *Journal of Management in Engineering*, 37 (4): 04021036. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000936.

Mostafa, K. T., S. Ojulari, and T. Hegazy. 2022. “Enhanced Repetitive Scheduling Formulation for Meeting Deadlines and Resource Constraints in Linear and Scattered Projects.” *Canadian Journal of Civil Engineering*. https://doi.org/10.1139/CJCE-2022-0029.

Nguyen, P. H. D., and D. Tran. 2024. “Optimizing Snow and Ice Route Removal Operations Using Vehicle Routing Problems and Geographic Information System.” *Journal of Cold Regions Engineering*, 38 (2): 04024001. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/JCRGEI.CRENG-721/ASSET/A8CEB2AF-DF78-4581-9C8B-4A9728FEB557/ASSETS/IMAGES/LARGE/FIGURE3.JPG.

Podolski, M., and B. Sroka. 2019. “Cost optimization of multiunit construction projects using linear programming and metaheuristic-based simulated annealing algorithm.” *Journal of Civil Engineering and Management*, 25 (8): 848–857. Vilnius Gediminas Technical University. https://doi.org/10.3846/JCEM.2019.11308.

Pushpakumara, T. D. C. 2021. “A Method of Finding the Best Route and Shortest Route to a Ready Mixed Concrete Plant Through Real Time Tracking System by using GIS and GPS.” *International Journal of Advanced Remote Sensing and GIS*, 10 (1): 3449–3462. Cloud Publications. https://doi.org/10.23953/CLOUD.IJARSG.499.

Saeed, F., K. Mostafa, and T. Hegazy. 2024a. “Applications of Travelling Salesman Optimization in Construction Scheduling.” *Canadian Society of Civil Engineering Annual Conference*, 443–451. Springer.

Saeed, F., K. Mostafa, M. Soliman, and T. Hegazy. 2024b. “Agent-Based Simulation of Multi-Crew Allocation to Scattered Repetitive Projects.” *Construction Research Congress 2024, CRC 2024*, 1: 1220–1228. American Society of Civil Engineers. https://doi.org/10.1061/9780784485262.124.

Siemiatycki, M. 2015. *Cost Overruns on Infrastructure Projects: Patterns, Causes, and Cures*.

Sixth Annual Report - CRUX Insights. 2023. *FOREWARNED IS FOREARMED -Anticipating Challenges and Mitigating Risks*.

Tomar, A., and V. K. Bansal. 2022. “Generation, visualization, and evaluation schedule of repetitive construction projects using GIS.” *International Journal of Construction Management*, 22 (6): 1104–1119. Taylor & Francis. https://doi.org/10.1080/15623599.2019.1683691.

Uzairuddin, S., and M. Jaiswal. 2022. “Digital monitoring and modeling of construction supply chain management scheme with BIM and GIS: An overview.” *Mater Today Proc*, 65: 1908–1914. Elsevier. https://doi.org/10.1016/J.MATPR.2022.05.160.

Wu, M., Q. Long, Y. Wang, Y. Chen, and M. T. Rahman. 2023. “Shortest Path Problem for Resource-Constrained Project Scheduling Based on Deep Reinforcement Learning.” *Proceedings - 2023 2nd International Conference on Machine Learning, Cloud Computing, and Intelligent Mining, MLCCIM 2023*, 91–97. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/MLCCIM60412.2023.00019.