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DATA-DRIVEN SIMULATION-BASED MODEL FOR PLANNING ROADWAY OPERATION AND MAINTENANCE PROJECTS

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ABSTRACT

Snow removal operations are required to maintain roadway safety during snowy winter conditions. Reliable plans outlining the dispatching of plow trucks must be made to deliver snow removal operations on time and within budget. Historical project performance data can be used to inform and facilitate decision-making processes associated with snow removal operations. This research proposes a data-driven simulation framework for planning snow removal projects considering weather and truck-related data collected by real-time sensors. An in-house developed simulation engine, *Simphony.Net*, is used to simulate operations based on input information extracted from mined sensor data. This model is capable of simulating plow operations to facilitate planning at both an operational and real-time level. What-if scenarios can be generated to simulate, predict, and optimize project and resource performance. A case study conducted in Alberta, Canada is presented to illustrate the practical application of the proposed method.

1 INTRODUCTION

Snow removal operations are crucial for maintaining roadway safety and accessibility following heavy snowfall (Kwon et al. 2017). The cost of specialized equipment, together with the labor expenses associated with their maintenance and operation, represents a considerable financial obligation for northern regions—in 2008, the City of Edmonton, Canada alone spent $46.6 million on its winter road maintenance program (Liu et al. 2014). Enhancing efficiency of snow removal operations through improved operation planning and management could considerably reduce snow removal-associated expenditures in these regions (Kinable et al. 2016).

However, approaches to winter road maintenance planning, particularly from a day-to-day operational or real-time level, continue to be highly experiential in nature. Decisions regarding when to dispatch plow trucks from truck maintenance shops, truck travel and plows routes, and the staffing of these vehicles are typically made based on weather forecasts and practitioner experience. The dynamic nature of snowfall, however, often requires practitioners to adopt a reactive management approach, dispatching trucks as required based on snowfall progression. This experience-based approach can lead to performance inefficiency, and ultimately, to increased project costs.

Vehicle-based automated location sensors (e.g., AVL, Ye et al. 2012), which automatically detect the location and speed of moving plow trucks, and advanced road weather information systems (RWIS, Boon and Cluett 2002), which monitor local weather and road surface conditions, have been developed to collect data in real-time. In practice, the data collected by vehicle location sensors are used for cost control purposes, while the data collected by weather information systems are used to detect the presence of snow at particular road sections. Notably, data captured by these technologies is not fully utilized.

While the collected truck- and weather-related data could be used to enhance the planning of snow removal projects, data-driven management systems capable of efficiently using both historical and real-time data to capture and analyze the performance of snow removal projects have yet to be developed. Hence, a data-driven simulation framework, which considers weather data, roadway specifications and priorities, truck speed, and plow route, that is capable of simulating (and potentially optimizing) snow removal plans, is proposed. The purpose of this research is to develop a planning tool for utilizing historical and real-time data to facilitate decision-making processes at operational and real-time levels that is designed to reduce the operation cost. Notably, this framework is capable of analyzing project performance of the simulated plan in terms of truck working hours and utilization. Furthermore, "what-if" scenarios can be generated to inform and improve future project performance at a real-time level. In the following sections, a literature review is provided and the current state-of-the-art of planning techniques for winter road maintenance is described. Next, the new methodology is proposed. Then, practical application of the proposed method is demonstrated through a case study. Finally, conclusions of this study are discussed.

2 LITERATURE REVIEW

Academic research and literature regarding the planning, design, and management of winter road maintenance operations has been recently summarized by Perrier et al. (2006a, 2006b, 2007a, 2007b). Their study underlies the current state of practice for winter road maintenance, which involves a variety of decision-making problems that must be addressed at a strategic, tactical, operational, and real-time level. Strategic-level decision-making involves the acquisition or construction of long-lasting resources intended to be used over a long period of time. This includes decisions related to the partitioning of a region or road network into sectors, scheduling of fleet replacement, and the location of facilities such as snow disposal sites and vehicle depots (maintenance shops). Tactical-level decision-making includes medium- and short-term decisions that are generally updated every few months and includes the assignment of sectors to snow disposal sites and the sizing of vehicle fleets. Operational-level decision-making is related to winter tasks that require ongoing attention on a day-to-day basis. Operational-level decisions may involve the routing and scheduling of vehicles and the staffing of such vehicles with crews. Finally, real-time level decision-making involves situations in which operations must be undertaken or altered rapidly (e.g., hours, minutes) in response to a sudden system change (e.g., equipment breakdowns, weather change). Modification of routes based on forecasted weather and traffic information is an example of real-time decision control. Notably, certain decision problems may be addressed from a variety of levels according to the planning horizon considered. For example, decisions related to the assignment of sectors to snow disposal sites could be considered tactical as they are generally updated every winter. However, when monthly adjustments must be made to account for snowfall variability, these decisions become operational in nature.

Optimization of the route by which a truck should travel from the maintenance shop to the road requiring plowing has been addressed extensively. Perrier et al. (2007) provided a comprehensive survey of optimization models and solution methodologies for planning the vehicle routes of snow plowing and disposal operations. Zhang (2009) formulated a capacitated arc routing problem using a heuristic procedure to find the optimum routes for vehicles. In their study, the objective was to minimize the total cost of snow emergency operations to achieve the desired level of service and social benefits. Salazar-Aguilar et al. (2012) introduced a synchronized arc routing problem and a mixed integer nonlinear problem for plow operations. The street segments with two or more lanes in the same direction were simultaneously plowed by different synchronized vehicles. Fu et al. (2009) developed a decision support model using integer programming for winter road maintenance activities that can be used to derive optimal service plans for a road network in real-time.

Haslam and Wright (1991) discussed the strengths and weaknesses of mathematical programming approaches. A multiple objective heuristic methodology was suggested for the design of routes for intrastate highway snow and ice control. Wright (1994) later described a computer-aided system for planning efficient routes (CASPER), which was designed to assist planners at the Indiana Department of Transportation during the design of vehicle routes for plowing and spreading operations. CASPER had a base model consisting of multi-objective search heuristics and network algorithms. Dussault et al. (2013) proposed a variant of the windy postman problem to identify the optimum route. In their methodology, they considered routes that attempted to avoid plowing uphill on steep streets and that took advantage of faster traversal time on plowed streets. However, this assumption requires the possibility of plowing against the direction of traffic. Perrier and Langevin (2008) presented a multiple hierarchical Chinese postman problem with class upgrading possibilities and vehicle road segment dependencies. Their study also discussed several extensions in real-life applications, such as turning restrictions and tandem service requirements. Simulation has also been used for strategic planning of winter road maintenance operations. Wells (1984) proposed a discrete-event simulation approach to assist planners in metropolitan and larger urban areas with the planning of various maintenance activities including salt and sand spreading, snow plowing, and snow disposal. The main goal of this approach was to facilitate the evaluation of the consequences resulting from varying the levels of service, resource availability, budget, and weather conditions. Damodaran and Krishnamurthi (2005) introduced a framework for salt spraying and snow plowing operations using a continuous simulation model. Changes in snowfall rate were considered to dynamically plan new truck routes for snow removal.

Simulation is an analytical tool that has been widely applied to model the behavior of construction systems (AbouRizk 2010). However, current simulation models of construction operations are limited by their inability to effectively incorporate data in real-time. Consequently, conventional simulation models, which are based on historical data, may not be reflective of real systems. Data collected by sensors can be analyzed to extract usable information and to inform simulation models of real system conditions, which can, in turn, be used to predict future project performance for decision-support purposes. There is a need, therefore, for the creation of models that are capable of incorporating historical and real-time data of truck routes and weather conditions for predicting, forecasting, and optimizing truck utilization and plowing hours. The following section introduces a new framework for data-driven simulation that is capable of providing decision support for planning snow removal projects of practical size and complexity.

3 METHODOLOGY

3.1 Proposed Data-Driven Simulation Approach for Snow Removal Operations

This section proposes a data-driven, discrete-event simulation framework that mimics snow removal operations (Figure 1). The purpose of developing this framework is to provide a general method for planning snow removal operations that can be applied to any simulation platform (not limited to *Simphony.Net*).

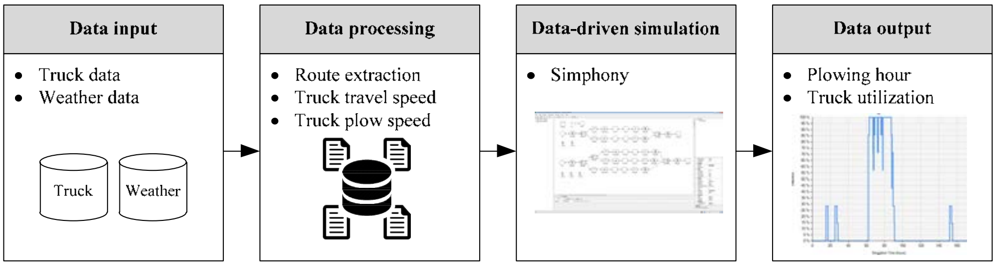


Figure 1: Proposed data-driven simulation approach for planning snow removal projects.

The inputs of the framework are based on the collection and evaluation of several plow-associated factors that are affected by the uncertainty associated with truck routes and weather conditions. The framework process is based on the use of an analytical tool such as simulation. The outputs of the framework are simulated plowing hours and truck utilization.

3.2 Data Input

Data collected from truck sensors and road weather information systems are summarized in Table 1. Historical truck sensor data were collected every 20 seconds and were recorded once a truck began to move. Weather information, specifically the precipitation status of road sections, was extracted from data collected by road weather information system sensors, which collected weather-based information every five minutes.

Table 1: Data collected by sensors.

Sensor	Truck	Truck	Weather	Weather	Weather	Weather	Weather
Type of data	Speed	Location	Air temperature	Road surface temperature	Wind speed	Precipitation detection	Precipitation rate
Unit of measure	km/hr.	(x, y) coordinates	degree Celsius (°C)	degree Celsius (°C)	km/hr.	yes/no	mm/hr.

3.3 Data Processing

The collected data of truck and weather sensors were mined to extract useful information. Truck sensor data were analyzed and filtered to extract the location and speed of the trucks. Data were examined and processed to extract the most frequently-used travelling routes for removing snow at particular road sections. Truck speeds, when traveling from the dispatch shop location to road section and when plowing the road, were also extracted. Data collected by weather sensors were filtered to extract the required weather parameter (e.g., precipitation detection).

3.4 Simulation

Based on historical truck performances and corresponding weather parameters collected from the sensors, various snow removal *scenarios* were defined. Each scenario was defined as a truck route that a truck could follow to plow the snow at a particular road section based on the precipitation status detected by particular sensors located within the maintenance area. All scenarios were designed to consider a variety of snow conditions at particular road sections, with one scenario occurring at one time. For example, if Sensor 1 detects snow precipitation yet Sensor 2 does not, an available truck will travel to and plow road sections closest to Sensor 1 first. Roads requiring plowing are determined, and a route is extracted based on historical performance. Notably, scenarios are only defined for instances where snow precipitation is detected. A database containing all scenarios, based on the comparison of precipitation levels between two successive precipitation records of each sensor, was constructed and was used as the data input of the simulation model. Using this database, the simulation model, which is based on discrete-event simulation, is run to simulate snow removal operations.

The simulation logic underlying the discrete-event simulation model is detailed in Figure 2. As truck allocation is planned on hourly basis, the flowing entities in the simulation model define the hours in a day. The resource elements are used to represent the available plow trucks in the maintenance shop. Following the hourly creation of an entity, the simulation model connects to the database to determine whether or not precipitation is detected. If there is no precipitation, the entity is destroyed and the scenario cannot proceed. If precipitation is presented, the scenario proceeds, resources are captured, and travel and plow activities are initiated. Resources (trucks) are released after the roads have been plowed.

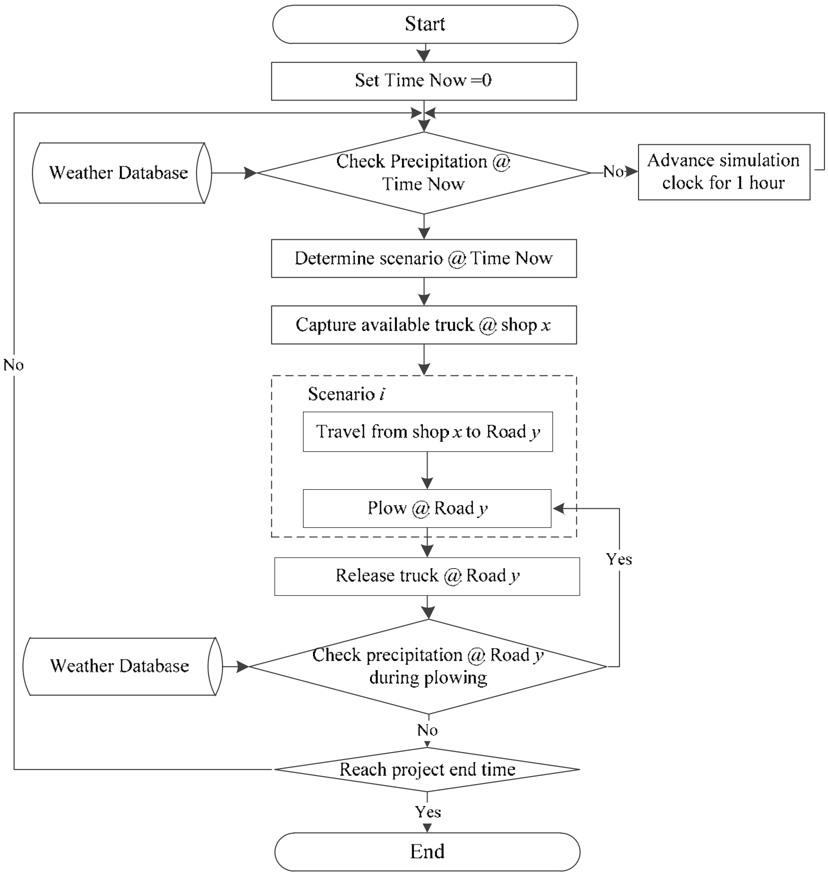


Figure 2: Simulation logic.

3.5 Output

The outputs of the simulation model, which are based on the forecasted weather data generated by the installed sensors or weather observatory, are truck working hours and truck utilization. Snow removal operations may also be optimized using the outputs of the simulation. For example, the optimum number of available plow trucks to minimize waiting time can be determined. The following section details a case study to demonstrate the application of the proposed framework within a practical setting.

4 CASE STUDY

A snow removal project based in Alberta, Canada was used to examine the functionality of the developed data-driven simulation model for planning snow plow operations in practice. This project required plowing of a roadway network consisting of 11 road sections. The road sections could be plowed by seven available plow trucks, which were dispatched from one maintenance shop.

4.1 Work Scope

The roadway network is illustrated in Figure 3. Two weather sensors were located as indicated. Road section, section length, and section priority (provided by the City of Edmonton), were outlined in Table 2. The priorities of particular road sections were determined based on road class, with higher traffic roadways receiving higher priority. All the roads in the considered area were bi-directional, with certain road sections having one or more lanes in each direction.

Table 2: Road specifications.

Road	1	2	3	4	5	6	7	8	9	10	11
Route	AB	BC	KJ	CPK	CE	CD	LM	MN	FG	HI	NO
Length (km)	28	30	12	14	25	32	21.5	19	21	17	9
Priority	1	4	3	1	3	4	1	1	1	1	1

Figure 3: Roadway network.

4.2 Input Modeling

Twelve scenarios for snow plowing were extracted from historical plow truck performance and corresponding historical weather data collected between 2016 and 2017. By considering the detection of precipitation by each sensor for two successive hours, various scenarios were defined as shown in Table 3. In this table, Scenario 1 indicates a condition in which Sensor 1 has detected precipitation at Time Now but not in the next hour and Sensor 2 has not detected any precipitation at both Time Now and the next hour. A condition in which both sensors have detected precipitation at Time Now and the next hour is defined as Scenario 7.

Table 3: Detection of precipitation.

Scenarios		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Time Now	Sensor1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
	Sensor2	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Next Hour	Sensor1	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No
	Sensor2	No	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes

Note: S=Scenario

For example, from the historical weather data is presented in Table 4, precipitation was detected on 4th of March at 07:00 and 08:00. These conditions are defined by Scenario 7, as precipitation was detected by both sensors at both times. Once a scenario has been assigned, historical truck performance data are used to determine the routes of the trucks for each scenario. The historical performance of all trucks is recorded in software used by the company to track assets of trucks. An example illustrating the performance of one truck is shown in Figure 4. Here, precipitation was detected by Sensor 2 at the affected road sections (6, 9, 10) so that a truck was allocated to these segments in the model. Allocation of trucks is determined in consideration of road section priority as presented in Table 5. All scenarios were designed to consider a variety of snow conditions at particular road sections, with one scenario occurring at one time. For example, Scenario 1 describes the condition where Sensor 1 detects snow precipitation yet Sensor 2 does not. In this case, the affected road sections, determined from historical performance, were (1, 2, 3, 4, 5), where one available truck will travel to and plow road sections (1, 2) and another truck will be allocated to plow road sections (3, 4, 5).

Table 4: Mined historical weather data.

Date	Time	Precipitation (Sensor 1)	Precipitation (Sensor 2)
3/1/17	12:00 AM	No	No
3/1/17	03:00 PM	Yes	No
3/2/17	01:00 AM	No	Yes
3/3/17	03:00 PM	Yes	Yes
3/4/17	07:00 AM	Yes	Yes
3/4/17	08:00 AM	Yes	Yes

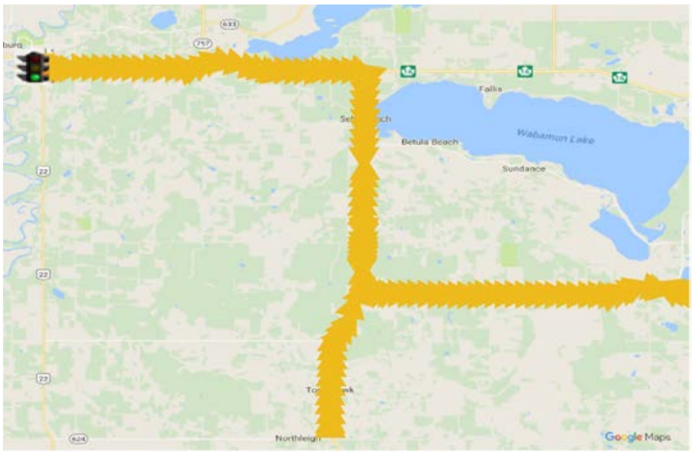


Figure 4: Route determination.

Table 5: Mined truck route.

Scenario	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	Truck 6
1	(2)(1)	(5)(4)(3)				
2	(2)(1)	(2)	(5)(4)(3)(5)			
3	(2)(1)(6)	(2)(6)	(5)(4)(3)(5)	(6)(11)(8)(7)	(6)(9)(10)	(2)
4	(2)(1)(6)	(5)(4)(3)	(6)(11)(8)(7)	(6)(9)(10)		
5	(2)(1)	(2)(6)	(5)(4)(3)	(6)(11)(8)(7)	(6)(9)(10)	
6	(2)(1)	(5)(4)(3)(5)	(2)(6)(2)	(6)(11)(8)(7)	(6)(9)(10)	(2)
7	(2)(1)	(5)(4)(3)(5) (4)(3)(5)	(2)(6)	(6)(11)(8)(7)	(6)(9)(10)	(2)(6)
8	(2)(1)	(5)(4)(3)	(2)(6)	(6)(11)(8)(7)	(6)(9)(10)	(6)
9	(6)(11)(8)(7)	(6)(9)(10)				
10	(6)(2)(1)	(6)(9)(10)	(6)(11)(8)(7)	(5)(4)(3)		
11	(6)(11)(8)(7)	(6)(9)(10)	(2)(6)	(5)(4)(3)	(2)(1)(6)	(6)
12	(6)(11)(8)(7)	(6)(9)(10)	(6)			

Mining of historical truck sensor data indicated that truck travel speed from the dispatch location to the plow road was *triangularly distributed* with a most likely, minimum, and maximum value of 20 km/hr., 15 km/hr., and 25 km/hr., respectively. Plow speed was also *triangularly distributed* with a most likely, minimum, and maximum value of 50 km/hr., 45 km/hr., and 55 km/hr., respectively.

Truck route and truck performance associated with each identified scenario is summarized in Tables 5 and 6, respectively. Travel and plow times were determined from route length and historical travel and plow speed.

Table 6: Specifications of all scenarios based on mined truck performance.

Scenario	Truck 1		Truck 2		Truck 3		Truck 4		Truck 5		Truck 6	
	Travel (km)	Plow (km)	Travel (km)	Plow (km)	Travel (km)	Plow (km)	Travel (km)	Plow (km)	Travel (km)	Plow (km)	Travel (km)	Plow (km)
1	1.5	116	0.5	102	-	-	-	-	-	-	-	-
2	1.5	116	1.5	60	0.5	152	-	-	-	-	-	-
3	1.5	180	1.5	124	0.5	152	0.9	162	0.9	108	1.5	60
4	1.5	180	0.5	102	0.9	162	0.9	108	-	-	-	-
5	1.5	116	0.9	124	0.5	102	0.9	162	0.9	108	-	-
6	1.5	116	0.5	152	1.5	184	0.9	162	0.9	108	*1.5*	60
7	1.5	116	0.5	304	1.5	124	0.9	162	0.9	108	1.5	124
8	1.5	116	0.5	102	1.5	124	0.9	162	0.9	108	0.9	64
9	0.9	162	0.9	108	-	-	-	-	-	-	-	-
10	0.9	180	0.9	108	0.9	162	0.5	102	-	-	-	-
11	0.9	162	0.9	108	1.5	124	0.5	102	1.5	180	0.9	64
12	0.9	162	0.9	108	0.9	64	-	-	-	-	-	-

4.3 Simulation Model Descriptions

In this research study, an in-house developed simulation engine, named *Simphony.Net 4.6* (AbouRizk and Hague 2009), was used to model the operations. Notably, the model consisted of 12 scenarios whose descriptions have been excluded due to paper size limitations. The number of servers indicates the number of available truck resources in the resource pool.

The database stores the forecasted weather information on an hourly basis over a seven-day period for a total of 168 hours. Table 7 summarizes the sample data stored in the database that is used for the simulation. The numbers 1 and 0 in the cells indicates whether a scenario occurs or not at a particular hour, respectively.

The simulation begins by creating entities for each scenario. The entities are then passed through the execute element to determine if precipitation was detected at a particular hour. If the database records indicate that precipitation was detected at a particular road section, the scenario is executed by capturing an available truck, which travels to and plows that road section. When plowing of the roads is completed for that scenario, trucks are released. The precipitation amount is calculated during the time the scenario was initialized and the current time. If snow continues to fall at that particular road section during plow operations, the released plow truck will be captured again to repeat the plow operations at that particular road section.

Table 7: Database for storing forecasted weather information.

Date	Time	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
3/1/17	12:00 AM	0	0	0	0	0	0	0	0	0	0	0	0
3/1/17	03:00 PM	1	0	0	0	0	0	0	0	0	0	0	0
3/2/17	01:00 AM	0	0	0	0	0	0	0	0	1	0	0	0
3/3/17	03:00 PM	0	0	0	0	0	1	0	0	0	0	0	0
3/4/17	07:00 AM	0	0	0	0	0	0	1	0	0	0	0	0
3/4/17	08:00 AM	0	0	0	0	0	1	0	0	0	0	0	0

Note: S=Scenario

4.4 Simulation Results

Simulation reports were generated after 50 simulation runs in a computer with the configuration of 64-bit operating system, 24 GB installed memory (RAM), 3.2 GHz CPU. The average simulation time was approximately 90 minutes for 50 runs. Reports included plowing hours (i.e., amount of time spent to plow the snow in seven days). Figure 5 illustrates the average plowing hours of all trucks with confidence intervals over the 168 hours. Notably, the period between 60 to 90 hours was associated with a period of heavy snowfall. Truck utilization, which is a measure of the percentage usage of the trucks over the simulation time, can also be tracked, monitored, and reported. In this case study, the utilization rate was 17% over the seven-day period (Figure 6).

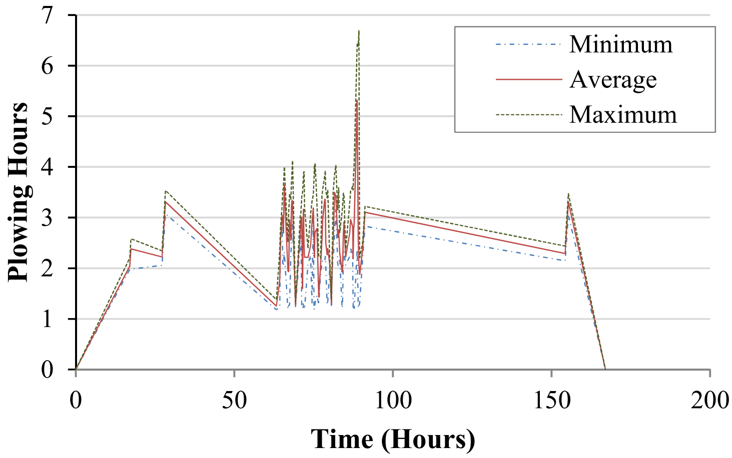


Figure 5: Plowing hours.

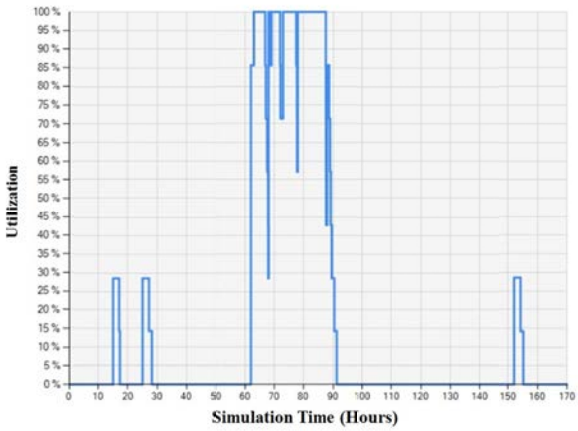


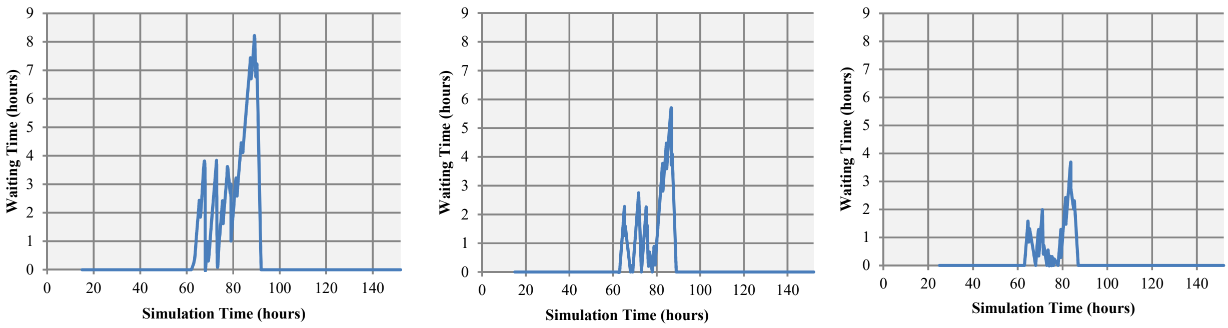
Figure 6: Truck utilization.

4.5 Model Verification and Validation

Historical data was used to validate the proposed model. Here, plowing hours predicted by the simulation model were compared to the historical plowing hours recorded by the company. The model's output was within 10% of the company's average plowing hours. Given that the simulation model was not intended to capture all factors affecting plowing hours, such as truck breakdown and maintenance, the difference observed is considered acceptable for practical purposes. These results confirm that the simulation model is capable of generating realistic and reliable results.

4.6 What-if Scenarios

To observe the impact of truck number on the time a road section must wait prior to the initation of plowing, sensitivity analysis was conducted as shown in Figure 7. When 6 trucks are available, the average wait time was 2.6 hours; when 8 trucks are available, the average waiting time is reduced to 0.8 hours. The sensitivity analysis results demonstrate that wait times can be reduced by altering truck availability, indicating that optimization of resources may decrease working hours. Figure 8 illustrates the simulated result of working hours that is obtained by modifying truck routes. The result demonstrates that changes to truck routes can increase working hours, suggesting that routes can be optimized to reduce working hours. The authors intend to explore this in future research endeavors.



(a) 6 Trucks. (b) 7 Trucks. (c) 8 Trucks.

Figure 7: Comparison of waiting time of scenarios with different number of trucks.

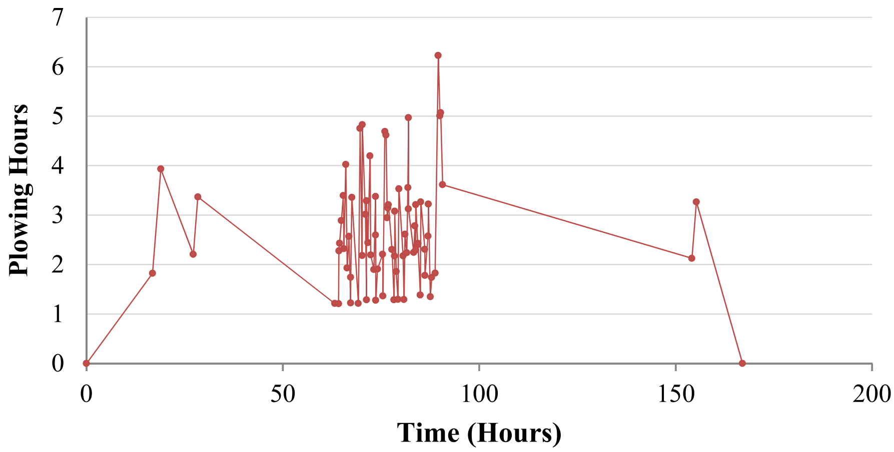


Figure 8: Plowing hours with alternative routes.

5 CONCLUSION

This research has developed a data-driven simulation framework for planning snow removal projects based on the integration of input of sensor data into a discrete-event simulation model. Weather sensors can be used to detect precipitation, while truck sensors can be used to collect the speed and location of plow trucks. To extract usable information from the data, data were mined to identify frequently-used truck routes along with the travel speed and plow time. This information was then used as inputs of the simulation model. The snow removal operations simulation model was developed using the in-house simulation engine, *Simphony.Net 4.6*. From forecasted weather data, truck dispatch plans for plowing snow at particular road sections can be simulated, and the total plowing hours and truck utilization rates can be predicted from the simulation results. To demonstrate its application, a practical case study was conducted based on a snow removal project in Alberta, Canada. A year's worth of historical snow removal operations data was used. The work scope was narrowed to 11 roadways with two associated weather sensors. Seven trucks with installed truck sensors were available to plow the snow. Based on historical precipitation detection data collected from the two weather-related sensors and historical truck route/speed/location data collected by the truck-related sensors, 12 snow removal operation scenarios were defined. The data-driven simulation model was used to reliably predict working hours and truck utilization based on forecasted weather parameters. What-if scenarios were performed to validate the simulation model. The proposed method can be used by project managers to make informed and reliable decisions at both an operational and real-time level so as to deliver forecasted snow removal plans on time and within budget. In future work, the proposed methodology may be extended to consider multiple maintenance shops with shared resources. The simulation model may also be modified to consider sanding operations concomitantly with plowing operations. Deicing may be also planned where required.

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