The numbers of occupants in the scenarios representing the current state of the building were obtained through observations on three non-consecutive days averaging their results. The following simulation assumptions were made for the occupants of the building:

- Average body radius for men (20-25 cm) and for women (19-23 cm) as per the study conducted by Smith and Brokaw (Smith 2008)
- Typical Movement Speeds for men (1.1-1.6 m/sec) and for women (1.05-1.45 m/sec) as per the study conducted by Smith and Brokaw (Smith 2008)
- Disabled Occupants are considered 1.65% of the building occupants as per 2011 study of the World Health Organization (WHO), UNICEF, and local civil society organisations which estimated the percentage of persons with disabilities to be approximately 11 %, or approximately 8.5 million persons (World Report on disability 2011). 15 % of the disabilities are related to mobility (Country profile on disability 2002).
- Speed Distribution for disabled occupants using a cane: Min 0.19 m/sec, Max 0.85 m/sec, Mean 0.56 m/sec, Standard Deviation 0.21 m/sec according to the study conducted by (Boyce 1999)
- Men, women and disabled occupants are randomly distributed as 49.175%, 49.175% and 1.65% of the entire building population respectively.

The second step of a simulation study is conducting the ten different simulation scenarios. Different combinations are used for conducting the simulation scenarios. The conducted scenarios include:

1. Compare between different evacuation plans for the current design of the building.
2. Adding an extra exit in the ground floor.
3. Adding an emergency exit with a fire escape in the first floor.

## RESULTS AND DISCUSSION

### Analysis of Conducted Scenarios

The average congestion factor improves when using the bridges for escape as this will decrease the congestion in the stair cases. The best result is 47% when all the second floor occupants escape through the bridge to the adjacent building and some of the first floor occupants use the bridge as well.

Conflicting points and high-density regions occur much more in the scenario in which occupants use only the stairs to evacuate. This is due to the congestion experienced by the evacuees in such case.

As shown in Figure 3, the minimum evacuation time is 00:03:00 (B4 and B10 which are the best two alternatives and B2). All Second Floor Occupants escape through the bridge while some of first floor occupants escape through the bridge. The maximum evacuation time is 00:03:56 (B7) which has an emergency exit in the first floor and some first and second floor occupants escape through the bridges to the adjacent building (randomly).

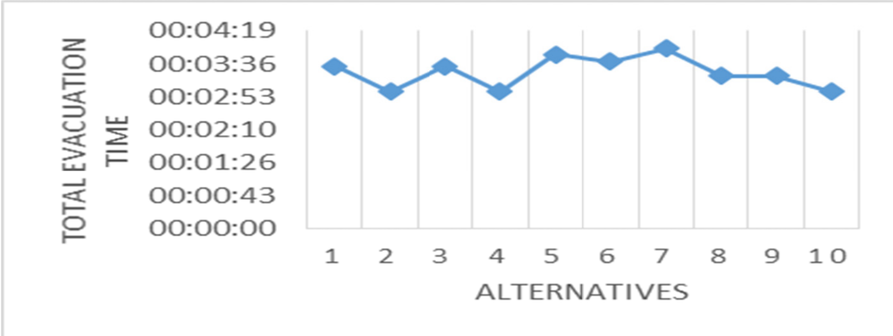


**Figure 3. Evacuation Time for All Alternatives**

## Correlation Matrix

A correlation matrix is constructed in order to measure the correlation between each two decision making techniques. The correlation matrix is calculated based upon Spearman's rank correlation coefficient for case 1. The Correlation matrix is depicted in Table 1. The maximum two spearman's rank correlation coefficients are between (WSM and SAW) and (MOORA and WSM) with values of 0.85 and 0.82, respectively. The minimum two spearman's rank correlation coefficients are between (MOORA and GRA) and (MOORA and SAW) with a value of 0.42. The values of the coefficient for WSM, GRA, SAW, MOORA are 0.83, 0.67, 0.72, and 0.66 respectively. The least value is associated with GRA, which means that its ranking is different from the other decision making techniques.

**Table 1. Correlation Matrix**

| | WSM | GRA | SAW | MOORA |
|---|---|---|---|---|
| **WSM** | 1 | 0.65 | 0.85 | 0.82 |
| **GRA** | 0.65 | 1 | 0.62 | 0.42 |
| **SAW** | 0.85 | 0.62 | 1 | 0.42 |
| **MOORA** | 0.82 | 0.42 | 0.42 | 1 |

## Case Study Recommendations

The alternative that was identified as the safest one was that in which all second floor occupants escape through the bridge while some of first floor occupants escape through the bridge and the rest of them use the stairs to the ground floor. These results highlight the fact that in order to increase the safety of the evacuees, all existing employees and building visitors need to be familiarized with the evacuation plan that includes using the bridges as exit to the adjacent building to seek refuge from the danger in the Administration Building.

## CONCLUSIONS

Regulating the occupants' movement and circulation patterns has always been a very challenging task to designers and architects in ordinary situations. When a fire emergency takes place, this task becomes even more challenging as the criteria to evaluate the circulation inside any structure expand to include the safety and well-being of the people inside it during their evacuation to a safe zone, under the conditions of large crowds all at once moving throughout the building heading to the exits. Numerous efforts are conducted to improve the evacuation performance of buildings. These are either qualitative/subjective methods that require experts evaluation, or are focused on minimizing the total egress time as the only point of comparison between buildings. The framework proposed in this research takes both qualitative and quantitative criteria into consideration for the assessment.

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# Reaction Time Optimization Based on Sensor Data-Driven Simulation for Snow Removal Projects

Parinaz Jafari[1]; Emad Mohamed[2]; Mostafa Ali[3]; Ming-Fung Francis Siu[4]; Simaan Abourizk[5]; Lance Jewkes[6]; and Rod Wales[7]

[1]Ph.D. Student, Construction Engineering and Management, Univ. of Alberta, Edmonton, AB, Canada T6G 2R3. E-mail: parinaz@ualberta.ca
[2]Ph.D. Student, Construction Engineering and Management, Univ. of Alberta, Edmonton, AB, Canada T6G 2R3. E-mail: ehmohame@ualberta.ca
[3]Postdoctoral Fellow, Construction Engineering and Management, Univ. of Alberta, Edmonton, AB, Canada T6G 2R3. E-mail: mostafaali@ualberta.ca
[4]Postdoctoral Fellow, Construction Engineering and Management, Univ. of Alberta, Edmonton, AB, Canada T6G 2R3. E-mail: msiu1@ualberta.ca
[5]Distinguished University Professor, Construction Engineering and Management, Dept. of Civil and Environmental Engineering, Univ. of Alberta, 9105 116 St., 5-080 NREF, Edmonton, AB, Canada T6G 2W2. E-mail: abourizk@ualberta.ca
[6]Project Coordinator, Ledcor Contractors Ltd., 7008 Roper Rd. NW, Edmonton, AB, Canada T6B 3H2. E-mail: lance.jewkes@ledcor.com
[7]Vice President, Ledcor Contractors Ltd., 7008 Roper Rd. NW, Edmonton, AB, Canada T6B 3H2. E-mail: rod.wales@ledcor.com

## Abstract

Reaction time of a snow removal project, which is defined as the duration between the time that snow begins accumulating at a road section and the time that snow is plowed, is a project performance indicator that can be used to evaluate the effectiveness of truck allocation strategies. While sensors, such as truck GPS (global positioning system) and weather RWIS (road weather information system), which track working hours and weather conditions, respectively, are used to collect large amounts of data, these data are not fully utilized to optimize reaction times of snow removal projects. In this research, the relationship between truck performance and weather information was analyzed. Sensor data were extracted, clustered, and refined; stochastic truck travelling speed and stochastic plowing speed were then mined and associated with the weather conditions of corresponding road sections. A data-driven, simulation-based optimization approach, which uses this mined data as input, was also developed to minimize reaction time. A practical case study of a project in Alberta, Canada, was conducted to validate and demonstrate the functionality of the proposed approach, which was simulated and optimized using the in-house simulation software, *Simphony.NET*. The resultant model allows project managers to predict the impact various truck allocation strategies on project time and cost to ensure that maximum project reaction time is minimized.

**Keywords**: Sensor data; Simulation; Optimization; Reaction time; Snow removal.

## INTRODUCTION

Snow removal projects are essential for preserving roadway safety and accessibility during the winter season of cold regions. These projects require specialized equipment, which represents a considerable financial obligation for northern countries. In 2008, the City of Edmonton, Canada, alone spent $46.6 million on its winter road maintenance operations (Liu et al. 2014). Service levels of snow plowing operations range from low to high, where a high level of service is defined by little snow accumulation prior to initiation of plowing, loss of an ice pavement bond during precipitation, and a rapid return to near normal road surface conditions after the precipitation ends (Perrier et al. 2006). Since service levels impact road conditions, municipalities often use performance indicators, such as reaction time, to ensure that minimum levels of service are achieved. Minimum reaction times for the City of Edmonton, based on average annual daily traffic (AADT), are detailed in Table 1.

**Table 1. Maximum Reaction Time Requirements**

| Class of Highway | Traffic Volume (AADT) | Maximum reaction time (hours) |
|---|---|---|
| A | >15000 | 2 |
| B | 7000–15000 | 4 |
| C | 5000–7000 | 4 |
| D | 2000–5000 | 4 |
| E | 1000–2000 | 6 |
| F | 500–1000 | 8 |
| G | 100–500 | 12 |
| H | <100 | 16 |

In general, increasing the level of service requires additional labor and equipment, which, in turn, requires a greater resource investment and increases project costs. Contractors must, therefore, ensure that required levels of service are achieved in the most efficient manner possible.

The improvement in sensing technology has had a tremendous impact on data collection in real-time. Two examples of these sensors are 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 [e.g., RWIS (Boon and Cluett 2002)], which measure weather parameters and road surface conditions. Currently, practitioners use collected sensor data for two purposes, namely cost control, where data collected by vehicle location sensors are used to track working hours of trucks, and weather forecasting, where data collected by weather information systems are used to detect the presence of snow at particular road sections.

While collected truck- and weather-related data could be used to enhance the performance of snow removal projects, computer simulations capable of efficiently capturing and analyzing such projects to achieve the required level of service have yet to be developed. Here, an optimization-based simulation framework, which considers weather data, roadway specifications and priorities, truck speed, and plow route, to simulate and optimize snow removal truck allocation strategies is proposed. Notably, this framework is capable of optimizing performance of the simulated plan by minimizing reaction time through modification of truck routes and quantities.

In the following sections, a review of the literature is provided and the current state-of-the-art of optimization techniques for winter road maintenance is described. Next, the methodology is proposed. Then, the practical application of the proposed method is demonstrated through a case study. Finally, conclusions of the study are discussed.

## LITERATURE REVIEW

Winter road maintenance projects involve multiple decisions that can be addressed using operations research methodologies. Optimization models that have been developed by researchers for snow removal operations can be divided into three categories: system design, snow disposal, and vehicle routing. The vehicle routing problem (VRP) was defined by (Laporte 1992) as the problem of defining optimal delivery or routes from one or several depots to a number of geographically dispersed cities or customers subject to side constraints. (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. (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. (Liu et al. 2014) introduced a mathematical optimization model based on the capacitated arc routing problem (CARP) and one meta-heuristic algorithm to minimize the total travel distance for snowplow operations. (Kinable et al. 2016) recommended a combination of heuristic and constraint programming to minimize the makespan of the schedule. (Perrier et al. 2008) presented a model and two heuristic solution approaches, based on mathematical optimization, for vehicle routing of snow removal operations to minimize the completion time of the operation.

Simulation is an analytical tool that has been widely applied to model the behavior of construction systems (AbouRizk 2010) and 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, and (Damodaran and Krishnamurthi 2005) introduced a framework for snow plowing operations using a continuous simulation model. (Mohamed et al. 2017) developed a real-time, data-driven simulation model, based on the historical performance of plow trucks, to more efficiently predict plow truck working hours and utilization.

Although simulation models for snow plowing operations have been built, optimization techniques to improve project performance have not been incorporated. This research proposes an optimization-based simulation framework for the vehicle routing problem of snow plow trucks that is designed to minimize project reaction time. Once a simulation model is built, optimization techniques can be used to identify the optimum solution, thereby assisting project managers with the optimization of project performance. The following section introduces a framework for reaction time optimization of snow removal operations.

## METHODOLOGY

This section proposes a data-driven, discrete-event, simulation-based optimization framework that can be used to optimize the reaction time of snow removal operations (Figure 1). The purpose of the framework is to provide a general method for optimizing the number of the trucks at each maintenance shop and identifying optimal routes to minimize reaction times.

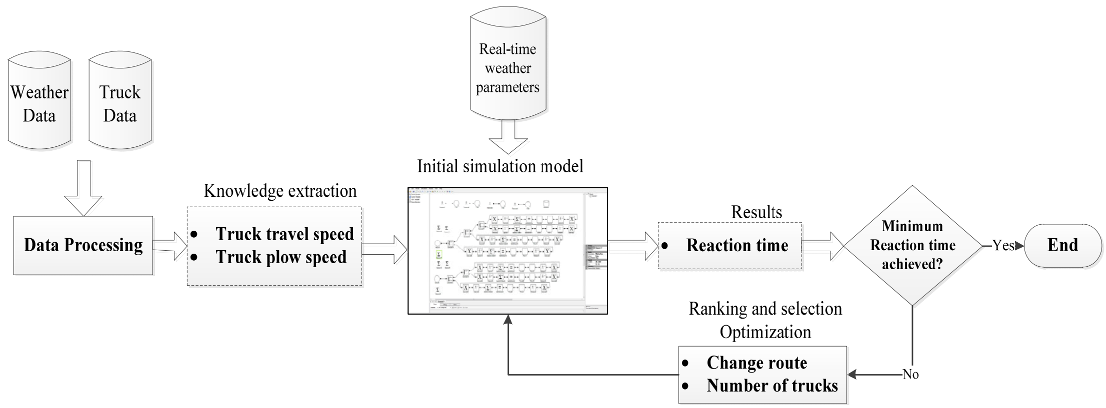


**Figure 1. Proposed framework**

## Data Input

The input of the proposed methodology is based on the collection of truck sensor and real-time weather data. Sensors attached to trucks collect speed and coordinates of trucks every 20 seconds after they begin to move. Weather information is recorded every five minutes by RWIS sensors, which are distributed in six locations throughout the maintenance area. The types of data collected are summarized in Table 2.

**Table 2. Data Collected by Sensors**

| Type of Sensor | Type of data | Unit of measure |
|---|---|---|
| Truck | Speed | km/hr |
| Truck | Location | (x,y) coordinates |
| Weather | Air temperature | Degree Celsius (°C) |
| Weather | Precipitation detection | Yes/No |

## Data Processing

Raw data gathered from truck and RWIS sensors were mined to extract useful information. Truck sensor data were analyzed and filtered to extract the location and speed of the trucks at certain times. The extracted truck speeds were classified into two categories: (1) travel speed of trucks from the dispatch shop to the road section and (2) plow speed of trucks. Data collected by weather sensors were filtered to extract useful weather parameters—in this case, precipitation detection. Correlation and regression analyses were conducted to determine the relationship between truck speed and weather parameters. Since each of the 6 weather sensors monitor a group of road segments, the truck speeds within the sensors' boundaries could be correlated with corresponding weather parameters. A multiple linear regression model with four variables, namely air temperature, dew point, relative humidity and wind direction, was used. Coefficient of the regression variables are provided in Table 3, where C1 is the coefficient of air temperature, C2 is coefficient of dew point, C3 is coefficient of relative humidity, and C4 is coefficient of wind direction. Notably, truck speed and weather parameters were not significantly related.

**Table 3. Regression Results**

| Sensor | R squared | C1 | C2 | C3 | C4 |
|---|---|---|---|---|---|
| 1 | 0.0076 | 1.4722 | -1.4742 | 0.3741 | 0.0076 |
| 2 | 0.0069 | 1.2982 | -1.2511 | 0.3053 | 0.0063 |
| 3 | 0.0111 | 2.8698 | -2.8876 | 0.6764 | 0.0053 |
| 4 | 0.0030 | 0.6130 | -0.5849 | 0.0675 | -0.0112 |
| 5 | 0.0068 | 2.0660 | -1.9577 | 0.3724 | 0.0010 |
| 6 | 0.0053 | 1.8006 | -1.7061 | 0.3535 | -0.0012 |

The historical truck sensor speed data were used to fit a distribution for two categories of speed. Various types of distributions were examined, and the goodness of fit relative to the historical data for each distribution was evaluated to identify suitable distributions. A Gamma distribution, with shape and scale parameters of 2.9878 and 2.6808, respectively, was determined to be suitable to model truck travel speed. In contrast, a Beta distribution, with first shape parameter 0.7303, second shape parameter 2.034, low value 41, and high value 64, was determined to be most suitable for modeling truck plow speed.

**Optimization-based Simulation**

Simulation optimization is defined by (Carson and Maria 1997) as the process of identifying the best input values from a set of possible values. Simulation is often chosen as a basis for handling decision problems associated with complex and uncertain systems (April et al. 2004). When it can be assumed that there are a fixed set of alternatives, ranking and selection procedures can be applied (Fu et al. 2005) for simulation optimization in two different ways. First, for inspecting a large set of alternatives, which involves the rapid exclusion of poor factors to obtain a more manageable set of alternatives, and second, for comparing selected solutions in a repeated algorithm (Fu et al. 2005).

(Carson and Maria 1997) have noted that the output of a simulation model can be used by an optimization technique to provide feedback when searching for optimal solutions. Here, two input variables affect the reaction time of the truck: the first is the route, which is comprised of a group of road segments, and the second is the available number of trucks at each shop as described in Figure 2. Notably, the effect of both variables must be optimized to minimize the reaction time.

In the simulation logic, the model runs by connecting to the database to determine whether or not precipitation was detected, and resource elements are used to represent the available plow trucks in the maintenance shop. An entity is created on an hourly basis in the model. If precipitation is detected and if trucks are available in the shop, they are dispatched to different routes. If not, the collect statistics is used to record the waiting time (i.e., the time between when precipitation is detected and when a truck is available). If there is no precipitation, trucks are not dispatched and the entity is destroyed.

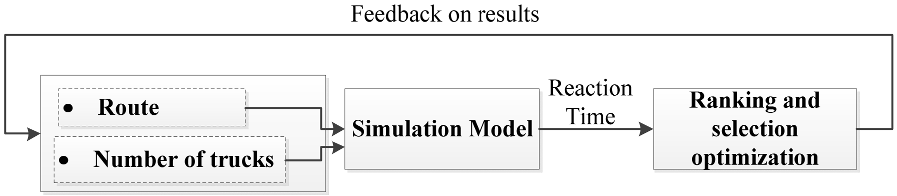


**Figure 2. Simulation optimization algorithm**

## CASE STUDY

To demonstrate implementation of the proposed methodology, a practical snow removal operation in Alberta, Canada, was examined. This operation required plowing of a roadway network consisting of 30 road sections.

### Work Scope

The roadway network is depicted in Figure 3. Six weather sensors, which collect weather parameters, are located in the area and are shown by yellow ellipses. Four maintenance shops, acting as truck dispatch locations, are also distributed in this area and are represented by red rectangles. The length and priorities of the road segments are provided in Table 4. Notably, all roads in this area are bidirectional, with certain road sections having one or more lanes in each direction.

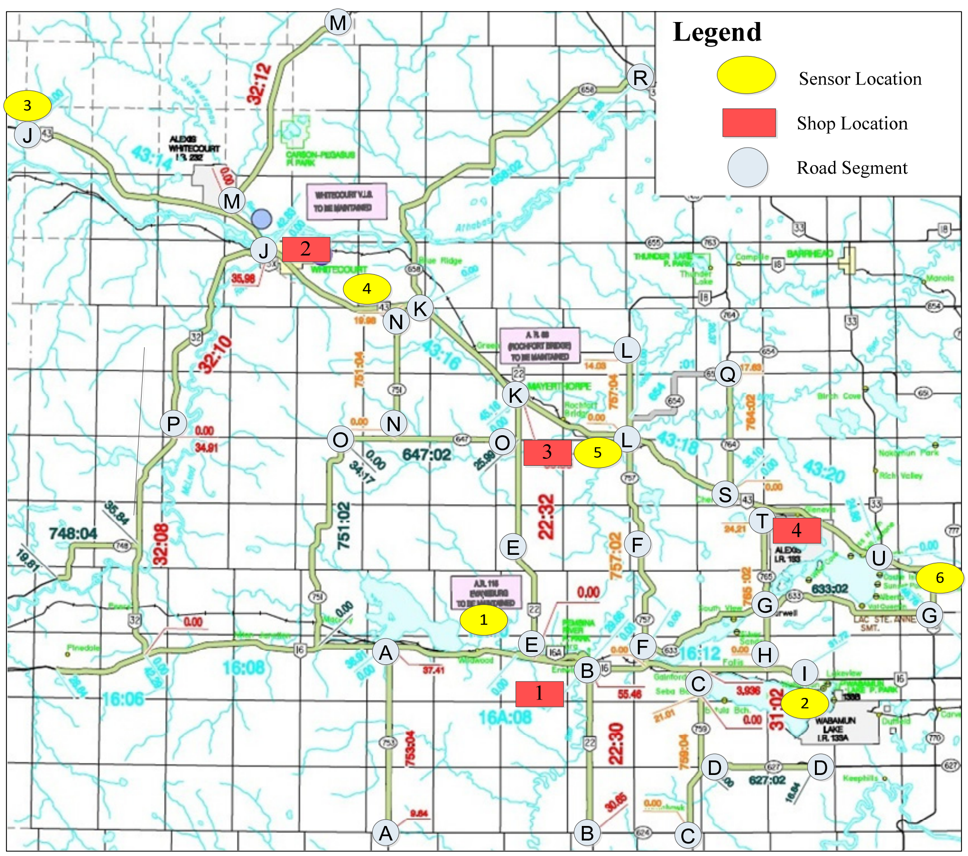


**Figure 3. Roadway network**