Using Discrete-Event Simulation to Support Building Asset Management: An Exploratory Case Study

Umberto GATTI¹, Omar EL-ANWAR², Giovanni MIGLIACCIO³, and Ken-Yu LIN⁴

¹ Research Associate, Department of Construction Management, University of Washington, 120 Architecture Hall, Box 351610, Seattle, Washington 98195
² Assistant Professor, Department of Construction Management, University of Washington, 120 Architecture Hall, Box 351610, Seattle, Washington 98195; PH (206) 543-4736; FAX (206) 685-1976; email: elanwar@uw.edu; and Lecturer, Cairo University, Structural Engineering Department
³ Assistant Professor, Department of Construction Management, University of Washington, 120 Architecture Hall, Box 351610, Seattle, Washington 98195; PH (206) 685-1676; FAX (206) 685-1976; email: gianciro@uw.edu
⁴ Assistant Professor, Department of Construction Management, University of Washington, 120 Architecture Hall, Box 351610, Seattle, Washington 98195; PH (206) 616-1915; FAX (206) 685-1976; email: kenyulin@uw.edu

ABSTRACT

Among the Washington State Department of Transportation’s (WSDOT) capital assets, Transportation Equipment Fund (TEF) shops provide a crucial service by ensuring proper care and maintenance of most of the state vehicles and equipment. Therefore, any reduction of TEF shop facilities capabilities could jeopardize not only WSDOT vehicles and equipment maintenance but also WSDOT’s ability to fulfill its core mission. Given the importance of TEF shops, this exploratory case study analyzes the building system failures that have occurred or are likely to occur in these facilities, and utilizes discrete-event simulation to investigate how WSDOT operations can be affected by these events. In particular, by creating a model capable of simulating the service operations performed in the TEF shops, this study quantifies the consequences of failures on the shop activities and road users. The aim of this paper is to describe the development and validation of the discrete-event simulation model and its associated data gathering efforts. Whereas, further building systems failure analysis and impact assessment are within the scope of another publication.

INTRODUCTION

Although transportation agencies’ building assets mostly consist of office buildings, they also include other unique types of buildings that directly support department operations, such as emergency and traffic management centers and vehicle repair shops (WSDOT, 2011). These buildings provide crucial support to the agencies’ core mission by (1) housing employees who design, construct, maintain, and operate roadways as well as (2) housing and maintaining vehicles and equipment necessary for inspecting and maintaining transportation assets. Due to several reasons, including funding cuts, building assets can rarely be comprehensively maintained and preserved (WSDOT 2012) and, therefore, failures are likely to occur and disrupt employees’ activities. Thus, to optimize the use of the available resources, it is compelling to develop innovative tools and methods capable of
determining how possible failure scenarios can impact employee’s activities and, eventually, road users. Such information could then be used by facility managers and decision-makers to develop maintenance and asset management programs and requirements that could reduce the risks of disruptions to employees and road users.

Excluding the ferry program related facilities and rest areas, Washington State Department of Transportation (WSDOT) occupies 3.2 million square feet of buildings. In particular, WSDOT leases 0.57 million square feet, and owns and manages the remaining 2.63 million square feet (WSDOT, 2011). WSDOT capital facility program focuses its efforts in managing 289 primary buildings with a minimum size of at least 2,000 square feet that house the department’s staff, vehicles, and equipment. These buildings account for more than 2.3 million square feet and include offices and crew spaces (WSDOT, 2010, 2012). Given the current economic situation, there is a lack of funds to properly maintain WSDOT facilities. However, it is not possible for the agency to program and direct its maintenance efforts in order to limit impacts on transportation system users because there are no standard tools or techniques available to determine how and to what extent this lack of maintenance could impact users.

Among WSDOT’s capital assets, Transportation Equipment Fund (TEF) shops are crucial in ensuring timely and effective care and maintenance of the majority of the state vehicles and equipment. Given the importance of these shops, the aim of this exploratory study is to investigate how failures caused by a lack of proper maintenance can impact WSDOT operations and users. In particular, the research team developed a discrete-event simulation model capable of simulating the repair and service activities during routine (i.e., non-failure) and failure conditions for the TEF shop located in Corson Avenue South (Seattle, WA). The team further utilized the develop model to analyze how failures occurring at that TEF shop can affect the TEF shop repair and service activities, and WSDOT snow and ice control (S&IC) operations. The Corson Avenue South TEF shop is the biggest in Washington State. It services most of the vehicles and equipment used in the Northwest Region (including Seattle-Bellevue and central King County), as well as vehicles from other areas when necessary.

RESEARCH DESIGN

Research activities in this project included data collection, modeling of work activities in bay areas, and analysis of the failure impacts. First, the data collection phase included gathering data about the TEF shop activities, facility conditions, and failures. Second, in the modeling phase, the research team used a discrete-event simulation tool to create a model capable of simulating the activities performed in the repair bays area during routine conditions. The developed model was validated against actual data. Third, in the analysis phase, the research team analyzed the failures that occurred at the TEF shop and determined failures’ consequences on TEF shop repair bays area activities and WSDOT S&IC operations using the validated model. Three analyses were performed as follows:

Analysis #1 – Loss in number of serviced vehicles (and equipment) by simulating the consequences of failures on the shop service activities.
Analysis #2 – Loss in number of serviced S&IC vehicles (and equipment) because of their importance during snowstorms.

Analysis #3 – Loss in number of plowed lane-miles in order to quantify how failures can impact road-users.

The scope of this paper is to describe in detail the data collection and modeling phases. Results of the analysis are presented in another practitioner-oriented publication. However, the aforementioned brief description of the analysis phase was to put the different research developments in context.

DATA COLLECTION

The objective of the data collection phase was to identify the activities performed, the procedures adopted, and the failures that occurred or can potentially occur in the shop. To this end, the research team utilizes four main sources for data. First, the research team visited the repair shop and examined the repair bays area. Second, several meetings were held with the TEF shop personnel in charge of managing the repair shop facility and activities. Third, the research team collected the list of work orders of all the serviced vehicles in the repair shop from 2009 to 2011 (over 20,000 work items). Fourth, the team analyzed the service requests for maintenance operations performed from 2009 to 2012 at the repair shop.

MODEL DESIGN

According to the collected information, the TEF shop personnel perform and oversee a wide range of activities. The model described in the following subsections focuses on the activities performed in the repair bays area (Figure 1), which include repairing, maintaining, and upgrading WSDOT vehicles.

Collected data analysis

Through a preliminary review of all the TEF shop work orders closed from 2009 to 2011, the research team identified over 170 different types of vehicles that were serviced, repaired, and/or upgraded. Generally, repair shop personnel close hundreds of work orders per month. The research team decided to analyze the work orders completed in January, February, and March of 2009, 2010, and 2011, because the winter season is critical for the repair shop activities where snowstorms can create serious issues to road-users. During the winter season, the repair shop has to be ready in preparing and servicing the S&IC vehicle fleet.

In order to obtain the information necessary for the model, the research team analyzed the data according to three steps, as shown in Figure 2. In the first step, the research team grouped the data to obtain homogeneous vehicle groups according to three parameters as exemplified in Table 1: vehicle characteristics (e.g., pick-up trucks vs. trucks); priority in being serviced; and, number of bays occupied while being serviced.
Further, to target S&IC vehicles, the vehicle groups containing SI&C vehicles were subdivided into S&IC vehicles and NO-S&IC vehicles (i.e., vehicles not used for snow and ice control operations). Second, for each vehicle group, the research team analyzed the work order durations to determine the frequency distribution (as shown in Figure 3). Finally, CurveFit 1.0, a probability distribution fitting tool, was used to determine which probability distribution could best fit each work order (Table 2).

**Service operation steps**

Any service operation performed on a vehicle can be represented as a series of steps (Figure 1). First, when a vehicle needs to be serviced, it is parked outside the TEF repair shop. Second, when repair bays are available, the vehicle can be selected for service in the repair bays area. The selection is based on the vehicle’s priority in being serviced and the number of repair bays necessary to service the vehicle. Third, when the vehicle is in a repair bay, it is serviced. Fourth, when the service is completed, the vehicle is taken out of the repair bays area.
Figure 2. Data analysis steps

**Step 1**
Data are grouped according to:
- Vehicle characteristics
- Priority in being serviced
- Number of bays occupied while being serviced

<table>
<thead>
<tr>
<th>Vehicle Group</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupied Bays</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 2**
Frequency distributions are determined for each vehicle group

**Step 3**
Best fitting probability distributions are determined
Table 1. Sample of Vehicle Groups’ Main Characteristics

<table>
<thead>
<tr>
<th>Vehicle group A</th>
<th>Vehicle group M (vehicle groups with S&amp;IC vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority: 2 (1 least important, 5 most important)</td>
<td>Priority: 5 (1 least important, 5 most important)</td>
</tr>
<tr>
<td>Number of occupied bays: 1</td>
<td>Number of occupied bays: 1</td>
</tr>
</tbody>
</table>

Vehicle types:
- **Vehicle group A**: 1 TON, CREW CAB; GAS; 4X2 ~ 1 TON; CREW CAB; DSL; 4X2 ~ 1/2 TON CREW CAB 4X4 ~ 1/2 TON, EXTENDED CAB; 4X2 ~ 1/2 TON, REGULAR OR EXTENDED C ~ 1/2 TON; CREW CAB 4X2 ~ 1/4 TON; EXTENDED CAB; 4X2 ~ 1/4 TON; EXTENDED CAB; 4X4 ~ 3/4 & 1 TON, CREW CAB; GAS; 4X ~ 3/4 TON; EXT CAB; DSL; 4X2 ~ 3/4 TON; EXT CAB; DSL; 4X4 ~ 3/4 TON; EXT CAB; GAS; 4X2 ~ 3/4 TON; EXT CAB; GAS; 4X4 ~ 3/4 TON; REGULAR CAB; DSL; 4X2 ~ PICKUP TRUCKS ~ SEDAN; GAS-ELECTRIC HYBRID ~ SEDAN; MID SIZE ~ STATION WAGON ~ PASSENGER CARRYING VEHICLE
- **Vehicle group M**: HERB SPRAY / ANTIICER; SKID MT ~ HERBICIDE SPARAYER; SKID MTD ~ HOPPER SANDER; 10/12 YARD; W/ ~ HOPPER SANDER; 5/6 YARD ~ HOPPER SANDER; LESS THAN 2 YD ~ SANDER; TAILGATE ~ HOPPER SANDER; HITCH MOUNTED

Figure 3. Example of frequency distributions for work orders

**Model structure**

Stroboscope discrete-event simulation software is used to model the operations performed in the repair bays area (Martinez 1996, 2001). The model incorporates two main activities, the Feed activity and the Service activity. The Feed activity represents the operation of parking the vehicles that need to be serviced outside the repair shop, while the Service activity represents the operations of selecting the vehicles to be serviced, servicing the vehicles, and moving the serviced vehicles out of the repair shop. The characteristics of the Feed and Service activities are described in Table 3.

It is necessary to repeat the basic series of activities and queues for each vehicle group to correctly model all the vehicles (Figure 4). This is attributed to the
fact that the characteristics of the Service activity (i.e., priority and duration) and the number of work orders are substantially different for each vehicle group (see Table 2).

### Table 2. Sample of Best Fitting Probability Distribution for Each Vehicle Group

<table>
<thead>
<tr>
<th>Vehicle Group A</th>
<th>Vehicle Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of work orders:</strong> 518</td>
<td><strong>Number of work orders:</strong> 49</td>
</tr>
<tr>
<td><strong>Work orders total duration:</strong> 1842 hr.</td>
<td><strong>Work orders total duration:</strong> 205 hr.</td>
</tr>
<tr>
<td><strong>Best Fitting Distribution:</strong> Gamma</td>
<td><strong>Best Fitting Distribution:</strong> Gamma</td>
</tr>
<tr>
<td><strong>Distribution Parameters:</strong> Alfa= 0.845, Beta = 4.185</td>
<td><strong>Distribution Parameters:</strong> Alfa= 0.845, Beta = 4.917</td>
</tr>
</tbody>
</table>

Figure 4 clearly shows that all the Service activities are linked to the same “available staffed bays” queue. This condition mirrors the fact that only a finite number of repair bays are available in the shop to service all the vehicles. Further, it is possible to determine for each Service activity a specific priority in receiving resources. Therefore, the simulation software tool is able to allocate the available staffed bays to the Service activities according to the specified priorities.

### Table 3. Logic, Conditions Needed to Start, and Outputs, of the Feed and Service Activities

<table>
<thead>
<tr>
<th>Activity</th>
<th>Feed</th>
<th>Service</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Logic</strong></td>
<td>This activity can process only one vehicle at a time from the “vehicle to be serviced” queue to the “vehicle ready to be serviced” queue;</td>
<td>This activity can process several vehicles simultaneously from the “vehicle ready to be serviced” queue to the “vehicle serviced” queue. Further, this activity has to obtain the necessary bays from the “available staffed bays” queue before processing a vehicle, and it gives them back to the queue when the vehicle has been processed.</td>
</tr>
<tr>
<td><strong>Conditions Needed to Start</strong></td>
<td>• One vehicle from the “vehicles to be serviced” queue</td>
<td>• One vehicle from the “vehicles ready to be serviced” queue • One or more bays from the “available staffed bays” queue</td>
</tr>
</tbody>
</table>
### Outputs

- One vehicle in the “vehicles ready to be serviced” queue
- One vehicle in the “vehicles serviced” queue
- One or more bays in “available staffed bays” queue (same amount of bays necessary to start the activity)

### Service Operation Steps

1. **Step 1**
   - The vehicle is parked outside the shop
2. **Step 2**
   - The vehicle is selected to be serviced
3. **Step 3**
   - The vehicle is serviced
4. **Step 4**
   - The vehicle is taken out of the shop

### Model Validation

The model accuracy is evaluated by comparing the number of vehicles identified to be serviced by the model with the collected data in several time periods. In particular, the following procedure was implemented:

- **Step 1.** Calculate the Expected average number of Serviced Vehicles in a specific time period (ESV) as:
  
  $$
  ESV = \frac{\text{Total number of serviced vehicles in 9 months}}{9\text{ months}} \times \text{Time Period}
  $$

- **Step 2.** Utilize the model in standard conditions to determine the total number of Serviced Vehicles (SV) during the model time period. To obtain statistically reliable results, the model iterated the simulation 1,000 times and the arithmetic means of SV values were calculated.

---

**Figure 4. Repair bays area model structure**
- **Step 3.** Evaluate the Model Accuracy as Model Error = ESV - Average SV

The simulation results are summarized in Table 4.

<table>
<thead>
<tr>
<th>Time period</th>
<th>ESV [vehicle]</th>
<th>SV [vehicle] – 1,000 Iterations</th>
<th>Model Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>St. Dev.</td>
<td>Max.</td>
</tr>
<tr>
<td>1 week</td>
<td>47</td>
<td>2.9</td>
<td>31</td>
</tr>
<tr>
<td>2 weeks</td>
<td>93</td>
<td>5.9</td>
<td>53</td>
</tr>
<tr>
<td>3 weeks</td>
<td>140</td>
<td>9.0</td>
<td>76</td>
</tr>
<tr>
<td>4 weeks</td>
<td>186</td>
<td>14.5</td>
<td>117</td>
</tr>
<tr>
<td>5 weeks</td>
<td>233</td>
<td>19.8</td>
<td>127</td>
</tr>
<tr>
<td>6 weeks</td>
<td>279</td>
<td>23.4</td>
<td>167</td>
</tr>
<tr>
<td>7 weeks</td>
<td>326</td>
<td>29.4</td>
<td>161</td>
</tr>
<tr>
<td>8 weeks</td>
<td>372</td>
<td>33.0</td>
<td>227</td>
</tr>
</tbody>
</table>

**DISCUSSION OF MODEL RESULTS**

The obtained results show that the model is able to predict the expected number of serviced vehicles within a maximum error of 5% in time periods from 1 week to 8 weeks. Therefore, it can be concluded that the model is accurate in capturing and simulating the service operations performed in the repair bays area of the TEF repair shop.

However, there are limitations to the model that need to be acknowledged. The model is built to represent a general case that involves (1) receiving a vehicle for service and opening a work order, (2) repairing the vehicle and recording the corresponding number of labor hours, and (3) closing the work order. However, there are other cases when a vehicle service is delayed because of reasons other than unavailability of maintenance bays, such as unavailability of parts. In such cases, the vehicle may either continue to be used by WSDOT personnel if the needed service was for minor issues or just wait in the TEF shop parking area if it needs service for major issues. In both cases, the service activity does not start until both the part and a bay become available.

Nevertheless, the accuracy of the model was sufficient for the purpose of the study, and accordingly, it was used to conduct the aforementioned three analyses in the “Research Design” section.

**CONCLUSIONS**

This paper presented the first component and the building foundation of a research project that aimed at supporting Departments of Transportation in assessing
the impacts of building failures on their operations and transportation system users. To this end this paper presented the development of a discrete-event simulation model to represent the repair and maintenance operations at the largest TEF shop in Washington State. The model was developed using Stroboscope.

In order to accurately model the repair and maintenance operations, the research team collected relevant information using various sources, including site visits, meetings, and records of thousands of work orders at the studied TEF shop. Statistical analysis was applied to the collected data and the resulting model was validated to yield an accuracy of at least 95% over an eight-week work period.

The presented model was further utilized to analyze the impacts of various building system failures on the repair and maintenance operations and eventually on Washington State transportation system users. However, this analysis is not within the scope of this paper.

ACKNOWLEDGEMENTS

The research team would like to acknowledge the funding support provided by Washington State Department of Transportation (WSDOT) (Sponsor Award # T4118-90). Secondly, the information provided by WSDOT personnel was the foundation of this research and this project would not have been possible without their help.

REFERENCES


