Resource Management of Bridge Deck Rehabilitation: Jacques Cartier Bridge Case Study

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Abstract: The condition and performance of bridges vary widely across North America. The large amount of expenditures on bridges needs significant efforts to optimize budget and resource allocation and to select the best rehabilitation or replacement method, which reduces project cost and duration. Simulation has been widely used in the construction area to optimize productivity and resource allocation. Current research optimizes resource combination for bridge deck rehabilitation projects using discrete event simulation. The Jacques Cartier Bridge redecking project is selected as a case study. Data related to productivity and duration of different activities were collected from the project. Probability distributions are fitted, which show the robustness of normal distribution to fit most variables. A simulation model is developed for this project in order to experiment with and perform sensitivity analysis. Based on the simulation results, an optimum resource combination of deck rehabilitation is obtained, which is [five teams, two saws, three old section trucks, and five new panel trucks] TSON 5235 with the unit (panel) cost of $747/h (direct cost only). The model developed is tested against real productivity where it shows reasonable results. The present research is relevant to both researchers and practitioners. It provides bridge redecking researchers with a real case study, a simulation model, and an approach to analyze projects. It also provides practitioners with an approach to optimize the usage of their resources considering direct project cost.

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Introduction

The Federal Highway Administration (FHWA) of the United States accumulated data on national bridges in the National Bridge Inventory (NBI) database, which is a collection of key information used to identify and characterize the type, usage, size, location, and condition of bridges in the United States The analysis of the NBI data shows that almost 40% of the 650,000 highway bridges are structurally deficient or functionally obsolete (Yanev 2005). Stidger (2005) reported that in 2004 the United States bridge deficiency rate was 25.4%; however, in 2005 it is 25%. On the other hand, Canada has 80,000 bridges of which about 50% are over 35 years old and are close to their designed life, which is 50 years (Ramcharitar 2004). Those figures show the huge amount of bridge rehabilitation and replacement work that has to be done in the near future in North America.

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Bridges require frequent maintenance and repair to keep them functional throughout their service lives (Elbeltagi et al. 2005). Rehabilitation and replacement costs of bridges in the United States average $7 billion annually (Yanev 2005); however, it is $0.7 billion annually in Canada (Mirza and Haider 2003). The limited funding of bridge rehabilitation requires an optimized budget allocation and the best selection of rehabilitation or replacement projects. State transportation officials are challenged to make good decisions, such as closing a bridge because it reached the point where its structural stability is questionable.

Previous research has proposed different methods for deck rehabilitation to optimize resource allocation, time schedule, etc. For example, the genetic algorithm model has been developed for a multiobjective optimization of bridge deck rehabilitation (Liu et al. 1997). However, most of the previous research considered long-term network-level maintenance planning rather than discussing the optimization of rehabilitation work at the project level, which concerns the construction method and resources allocation.

During the execution of the maintenance activities, the interruption to end users of the bridge should be kept to a minimum. In most cases of deck-replacement projects, the work is carried out at night with some or all lanes closed, and the traffic should be reopened in the morning. These severe constraints led to solutions which incorporated large precast post-tensioned concrete panels that were designed and detailed to allow them to carry full design live load immediately after they had been erected (Gauvreau 2007). Such design of the new deck always requires using cranes to lift the old deck and install the new panel.

Once rehabilitation activities are decided, officials have to decide the closing time of day and duration so that the effect on users and businesses can be reduced as much as possible. Therefore, deciding the suitable working time on the deck is crucial to officials, contractors, users, and surrounding businesses. Consequently, replacement activities' sequence, type of equipment, and team organization should be studied to help in the decision making process. Well allocated resources can help in reducing the project duration and improving productivity.

The Lions' Gate Bridge, which is the longest suspension bridge in Western Canada, is an interesting example of a major replacement project. In 2000 and 2001, the corroding suspended structure of the bridge was progressively replaced in 54 segments, typically 20 m (64 ft.) long. It is the world's first replacement of the complete suspended structure of a major suspension bridge during short night-time closures (typically 10 h). A typical replacement operation consisted of closing the bridge to traffic at 8:00 p.m., cutting 20 m sections of the deck and stiffening trusses, lowering the section to a barge 60 m below, lifting a new section from the barge, connecting it into place, and opening the bridge to traffic by 6:00 a.m. (Buckland and Taylor Ltd. 2006). Similar methods of redecking projects are carried out in North America, such as the Champlain Bridge redecking project in 1993, which involved replacing the original concrete deck and installing 254 new steel deck panels; the Laviolette redecking project (Breault 2006), and the I-95 James River Bridge Restoration Project in 2002 (I-95 James River Bridge 2002). The redecking construction sequence is similar, which is cutting and removing the old section, transporting the new panel, and installing the new panel using cranes.

Similarly, the Jacques Cartier Bridge, Montreal, connects Montreal Island to Longueuil City in the south. It is an important artery to users who are working in Montreal and living in Longueuil and vice versa. Approximately, 43 million vehicles cross this bridge every year. Exactly 1,680 prefabricated deck units, representing a surface area of about 62,000 m^2, were installed principally at night in order not to block traffic during the day.

Based upon the aforementioned discussion, the Jacques Cartier Bridge deck rehabilitation activities have to be optimized so that project duration and traffic disruption are minimized at the project level. Therefore, the present research aims at designing the bridge deck replacement productivity model and optimizing the use of available resources so that minimum project duration and traffic disruption are guaranteed. In addition, the best resource combination can be selected based on unit cost and productivity.

Discrete Event Simulation

Discrete event simulation has been widely used in the construction area in order to plan processes, allocate resources, and detect conflicts. Simulation is the experimentation with a model represented in a computer program that provides information about the system being investigated (Zayed and Halpin 2001). The simulation approach of analyzing a model can be used instead of the analytical approach in which the method of analyzing the system is purely theoretical. Simulation attempts to duplicate "real-life" engineering problems with computer models using actual data from the engineering situations being examined. The objectives of simulation are usually to determine the impact of a change of input on the whole system or on local parts of the system. It can be used before the construction of a system to evaluate the performance, to estimate system throughput or the delay of the system, and to identify any potential bottlenecks in the system (Hajjar and AbouRizk 1999; Martinez 1998; Zayed and Halpin 2001). Simulation can also be used to determine the optimum layout and capital and overhead requirements for a system.

Several simulation systems have been developed to model and analyze construction processes and to help decision makers. CYCLONE (Halpin 1977), Simphony (Hajjar and AbouRizk 1999), and Stroboscope (Martinez 1998) are popular software used in the construction area. They have proven to be effective and efficient in simulating various construction projects. AbouRizk et al. (1999) modeled and analyzed the tunneling process using the special purpose tunnel template developed with Simphony. Zayed and Halpin (2001) applied simulation to concrete batch plant operations in order to analyze alternative solutions of resource management using MicroCYCLONE. Martinez et al. (2001) applied the simulation to air-side airport operations to optimize resource allocation. However, a simple evaluation of performance is often insufficient in real projects. Simulation-based optimization has received considerable attention from both simulation researchers and practitioners to solve complex problems involved in construction. Simulation-based optimization is the process of finding the best values of some decision variables for a system where the performance is evaluated based on the output of a simulation model of this system (Olafsson and Kim 2002). The present paper provides a simulation model for bridge redecking, which is flexible and can be modified to suit other types of redecking projects. It also provides an approach to optimize the resources allocation with a rough cost estimate of the direct cost item in the project. The Jacques Cartier Bridge rehabilitation project is further discussed in the next section.

Jacques Cartier Bridge Case Study

Jacques Cartier Bridge, located in Montreal, is chosen as the subject of this research. It is a five-lane bridge of about 2.7 km in length, spanning the St. Lawrence River between the cities of Montreal and Longueuil (Fig. 1). Over the last 70 years, the old reinforced concrete bridge deck had seriously suffered from the increase of number and load of trucks as well as the deicing salts used extensively since the 1960s. Consequently, the deck was replaced in two construction seasons (April–October) during 2001 and 2002. With a total project cost of approximately $120 million (Canadian), this project represents the biggest bridge rehabilitation project ever carried out in Canada. Therefore, optimizing resources in order to increase productivity and reduce costs accordingly is essential for future redecking projects. Thus, there is a need to develop a framework or an approach that optimizes project resources to be used as a preconstruction planning approach for solving future project problems. The deck reconstruction method was developed on the basis of the following main objectives (Zaki and Mailhot 2003):

- Minimize inconveniences to as many users as possible;
- Construct a new highly durable deck (design service life greater than 50 years);
- Ensure safety of both users and workers;
- Minimize negative impacts to the environment; and
- Complete the deck replacement during 2 construction years.

The new deck is constructed of precast, prestressed, and post-tensioned panels made of high performance concrete which were prefabricated in a temporary plant installed near the south end of the bridge. Due to the spatial and temporal constraints, deck replacement had to be done at night during weekdays from 8:30 p.m. to 5:30 a.m. The case study focuses on the two activi-

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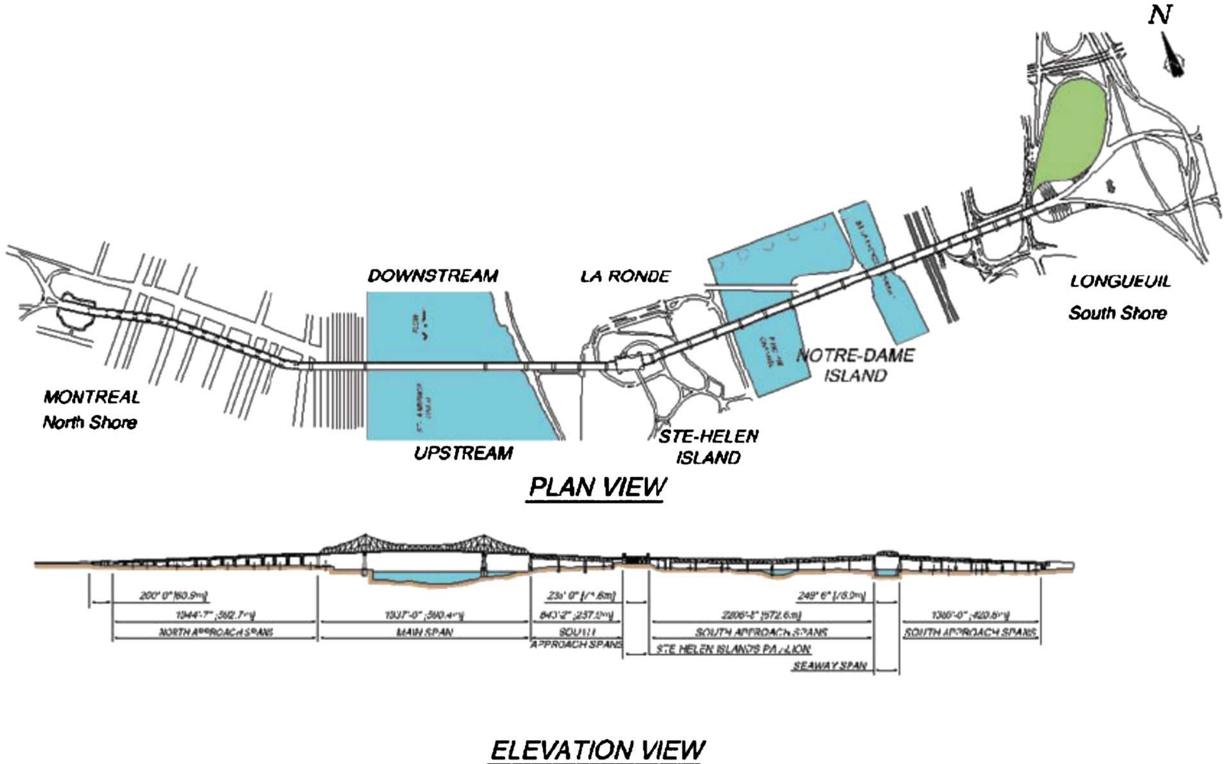

Fig. 1. Plan and elevation views of Jacques Cartier Bridge (PJCCI 2007)

ties of removing existing deck sections and installing new panels in the main span of the bridge. These two activities were critical to the success of the project from the point of view of spatial and temporal constraints. The existing deck was removed by saw cutting the deck into sections similar in dimension to the new panels. New panels were transported form the precasting plant near the south entrance of the bridge. Each existing deck section was removed and a new panel was lifted by two 60.5 ton self-propelled telescopic cranes placed at opposite ends of a panel (Fig. 2). Typically, the contractor decided to use two teams working in parallel (concurrent) at different parts of the bridge. Two types of semitrailer trucks were used to transport the old sections and new panels. Fig. 3 shows a schematic representation of the worksite layout during the deck replacement.

Data were collected from the main contractor of the deck rehabilitation project, which includes duration of different project activities (e.g., cutting, removal, and transportation of old sections as well as transporting, unloading, and installing new panels); sequence of operation for each team (construction processes); space and logistic obstacles or constraints that might face each team; hours of operation; and features of each activity. Probability distribution of the duration of each activity was developed to experiment with in the simulation process.

Statistical Analysis of Probability Distributions

Before using simulation to build the required model so that resources can be better managed, the probability distribution of each task in the rehabilitation process has to be determined. Based upon 180 data points, the probability distributions of tasks involved in the rehabilitation process are developed. Fig. 4 shows the histograms and normal curves that best fit the available data. The tasks involved in this analysis are categorized under two major processes: (1) cut and dump old sections; and (2) fabricate and install new panels. The tasks involved in the first process (cut and dump old sections) are: cut sections; load sections on trucks; trucks travel to dumping area; unload sections; and trucks return after dumping the sections to get another set. On the other hand, the tasks involved in the second process (fabricate and install new panels) are: load panels in the fabrication shop; trucks travel to installation site; unload and install panel; trucks return to get other panels; then, the team [fleet of equipment (cranes) and labors] moves to another section location (repositioning). Fig. 4 also shows the probability distribution for installing a complete new panel: cut and load old section, install new panel, and move to another location (repositioning). The mean value of such a process is 75.87 min/panel; however, the standard deviation is 5.52 min. In addition, the limits of 95% confidence interval for panel duration are 74.80 and 76.94 min.

Team productivity in panels per day is statistically analyzed, which shows that normal distribution is the best fit with mean value of 8.16 panels/day and standard deviation (SD) of 3.45 panels/day. The lower and higher limits of 95% confidence interval for productivity are 7.65 and 8.66 panels/day, respectively. Similarly, the tasks involved in the rehabilitation processes are statistically analyzed to check their best probability fit as shown in Table 1. It shows the mean and standard deviation of each normal probability fit for each task. Three tests are performed to check the best distribution fit of each task: (1) Chi-squared (Chi-sq); (2) Anderson–Darling (A-D); and (3) Kolmogorov–Smirnov (K-S). Two hypotheses are generated to test the data fit: (1) null hypothesis (H_0): the data follow a normal distribution; and (2) alternate hypothesis (H_a): the data do not follow a normal distribution. The critical value (CV) for each test at 1% significance level is shown in Table 1: CV-Chi-sq=29.14;

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Fig. 2. Installing panels on bridge (Zhang and Hammad 2006)

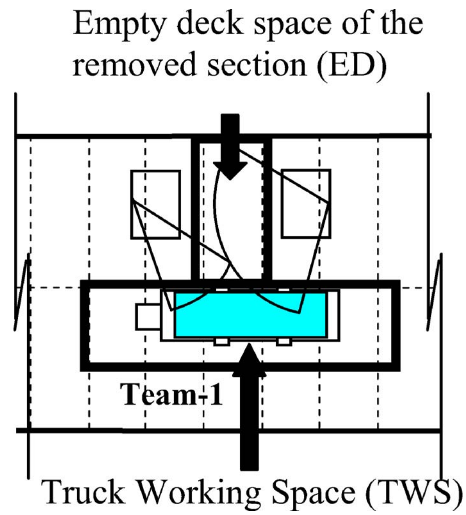

Fig. 3. Worksite layout for team of two cranes and truck on bridge

CV-A-D=1.03; and CV-K-S=0.08. In addition, Table 1 also shows the test statistics (TS) for these tests. For example, the TS for cut old section task are TS-Chi-sq=13.17, TS-A-D=0.3155, and TS-K-S=0.0476. It is noticed that the TS value is lower than the CV for all tests, which reflect the acceptance of null hypothesis at significance level (α) equal to or less than 15%. The lower and higher limits of 95% confidence interval for cut old section task are 17.65 and 18.26 min, respectively. Similarly, the rest of the tasks are analyzed as shown in Table 1.

The *P* value is another statistical parameter that can be used to show the fitting robustness of probability distribution to the available data. It is defined as the probability of generating a test statistic greater than or equal to TS from a new set of *N* samples, which are drawn from the fitted distribution. As the *P* value tends to zero, it will be less confident that the fitted distribution could possibly have generated from our original data set. Conversely, as the *P* value approaches one, the null hypothesis (H_0), which assumes that the fitted distribution generates the data set, cannot be rejected. Accordingly, the *P* value for installing a complete new panel process is 0.9211, >0.25, and >0.15 using Chi-sq, A-D, K-S, respectively. Based upon the aforementioned discussion, the *P* value tends to one, which means that the fitted normal probability is accepted. Similarly, the *P* value for the rest of the tasks and productivity also tend to one, which shows the robust fit of the normal distribution to most available data. Finally, the data are analyzed and probability distributions are fitted to be ready for simulation usage.

Case Study Analysis and Simulation Model Building

The construction simulation software packages, such as MicroCYCLONE, Strobocope, and Simphony, use similar simulation engines, which apply the queueing system approach in solving the problem. Therefore, using any of them will provide the basic necessary information required by the user. Fig. 5 shows a simulation model for the redecking project using MicroCYCLONE, which is selected because of its availablility and similarity of its simulation engine to other recent simulation software such as Stroboscope and Simphony. In MicroCYCLONE, the active-state rectangular nodes represent tasks; idle-state circles represent delays or waiting positions for resource entities; and directional flow arrows represent the path of resource entities as they move between idle and active states. Tasks can be executed only when all the required resources are available. For example, the task “Dumping” (Node 13) is the task of dumping an old section of the deck in the dump area. It takes an average time of 5.23 min and needs two resources: “Truck waiting for dump” (Node 11) and “Forklift waiting” (Node 12). After the dumping of one section is finished, these two resources are released: the truck will return to the bridge (Node 14) and the forklift will go back to an idle state (Node 12).

Resources required in this project include: teams (two cranes and crews), saws (including operators), trucks (including the drivers) for carrying old sections, trucks (including the drivers) for carrying new panels, a small crane for loading new panels in the plant, a forklift for dumping the old sections in the dump area, empty deck space of the removed section, truck working space, etc. The model developed consists of several cycles; three of the main cycles are described as follows:

1. Old section cycle: The existing deck is cut by saw into sections. Empty trucks are waiting for the team to load old sections. After loading, the truck transports the old section to dump area. After dumping, the truck goes back to the bridge for loading the next old section;
2. New panel cycle: New panels are transported from the plant to the bridge. The same team for removing an old section also installs a new panel. After installation, the truck goes to the plant to load a new panel; and
3. Team cycle: Teams are located at different locations on the bridge for removing old sections and installing new panels. They move to the next location on the bridge after they finish installing each panel.

Table 2 shows the tasks involved and their durations [mean (μ) and standard deviation (σ)]. These durations are input to the MicroCYCLONE program to simulate the proposed model in Fig. 5. When one team of cranes, one truck to carry new panels

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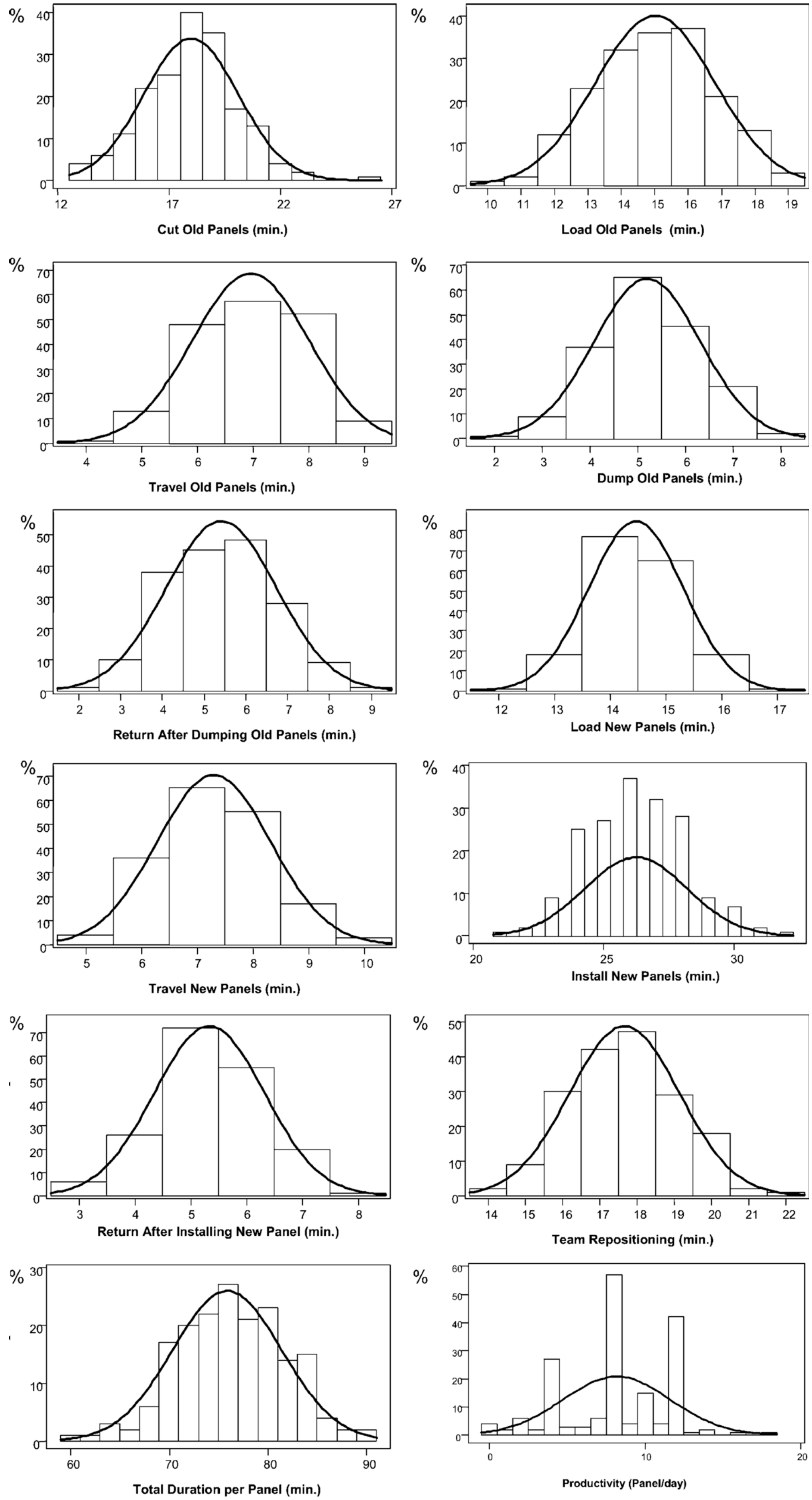

Fig. 4. Probability distribution for cutting old and installing new panels

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Table 1. Various Activity Duration Fits for Rehabilitation Process

	Statistical analysis of normal distribution fit									
Statistical item	Cut old	Load old	Travel old	Dump old	Return old	Load new	Travel new	Install new	Return new	Reposition
□ (min)	17.95	15.03	6.95	5.23	5.42	14.46	7.31	26.20	5.31	17.69
□ (min)	2.11	1.71	1.00	1.06	1.30	0.81	0.99	1.89	0.94	1.42
TS-Chi-sq	13.17	5.50	15.00	16.17	11.33	10.67	7.00	7.83	13.00	17.50
TS-A-D	0.32	0.15	0.53	0.31	0.30	0.32	0.33	0.31	0.27	0.22
TS-K-S	0.05	0.03	0.05	0.04	0.04	0.05	0.04	0.04	0.05	0.03
P value-Chi-sq	0.51	0.98	0.38	0.30	0.66	0.71	0.93	0.90	0.53	0.23
P value-A-D	>0.25	>0.25	$0.05 <= p <= 0.1$	>0.25	>0.25	>0.25	>0.25	>0.25	>0.25	>0.25
P value-K-S	>0.15	>0.15	$0.025 <= p <= 0.05$	>0.15	>0.15	>0.1	>0.15	>0.1	>0.15	>0.15
Confidence (C) interval @ 95%	0.31	0.25	0.15	0.16	0.19	0.12	0.14	0.28	0.14	0.21
□−C (min)	17.65	14.78	6.80	5.07	5.23	14.34	7.16	25.93	5.18	17.48
□+C (min)	18.26	15.28	7.10	5.38	5.61	14.58	7.45	26.48	5.45	17.90

Note: CV-Chi-sq@15% = 19.41; CV-A-D@15% = 0.5586; and CV-K-S@15% = 0.0575; data points = 180.00; H_0 = data follow a normal distribution; and H_a = data do not follow a normal distribution.

(NP), one truck to carry old sections (OS), and a cutting saw are used, the resulting system productivity is 0.89 panels/h with a unit cost (the cost includes all related costs for removing one old section and installing one new panel) of $1,071.21/h. This will generate eight panels/day of 9 working hours (8:30 p.m. to 5:30 a.m.). The contractor was working 9 night hours with two shifts; therefore, no rest time was allowed in order to complete the project on time.

Space requirement for rehabilitation work on the bridge is analyzed, based upon project manager experience, to avoid space conflicts among working teams. It is assumed that the space required for each team is 60 m along the length of the bridge.

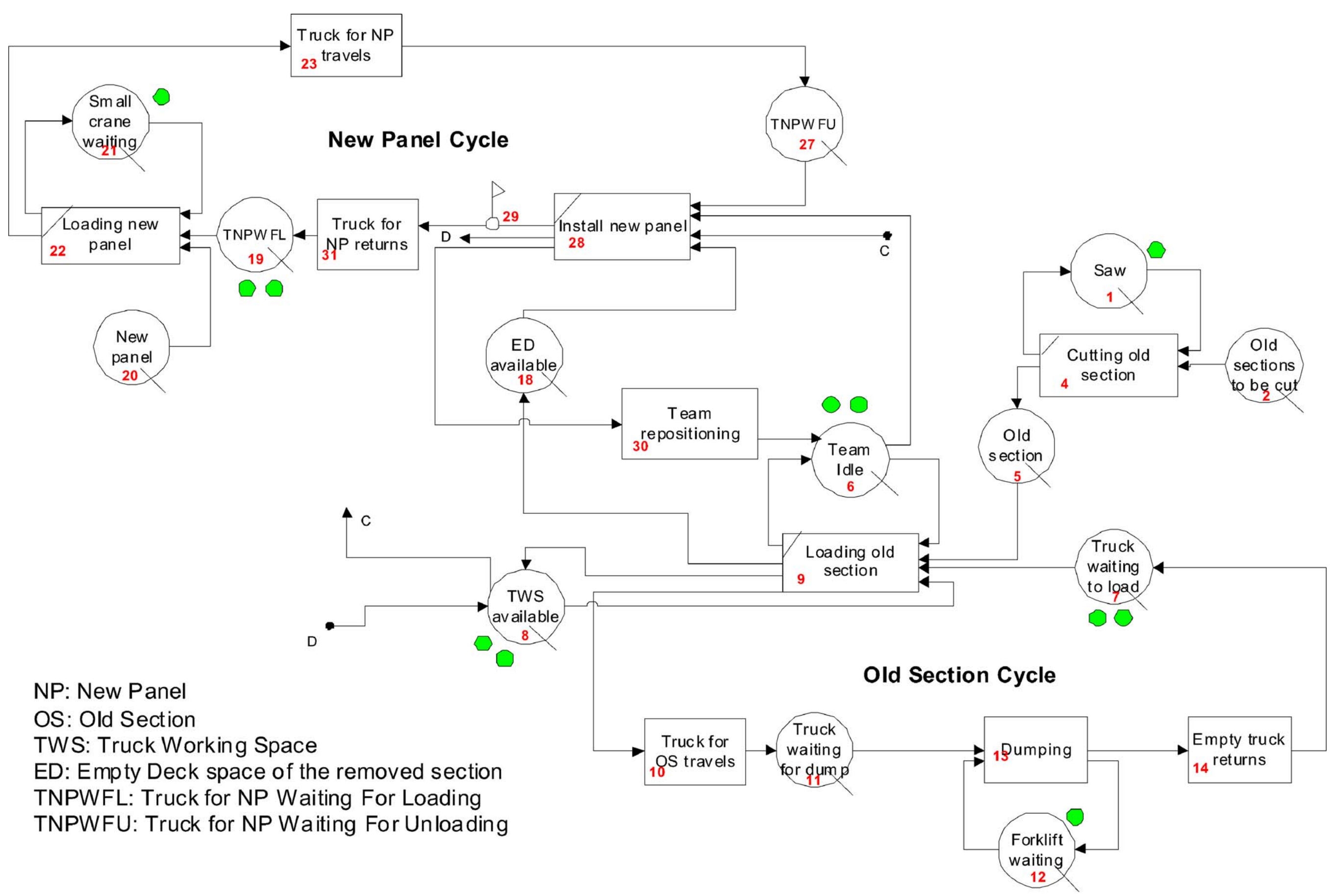

Fig. 5. MicroCYCLONE model of Jacques Cartier Bridge redecking project

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Table 2. Task Durations and IDs Used in MicroCYCLONE Model

Activity	Task ID	Task description	Task duration (min); normal distribution [μ(σ)]
Remove old sections	4	Cut old section	17.95 (2.11)
	9	Load old section	15.03 (1.71)
	10	Truck with old section travels to dumping area	6.95 (1.00)
	13	Dump old section	5.23 (1.06)
	14	Empty old-section truck returns to bridge	5.42 (1.30)
Install new panels	22	Load new panel	14.46 (0.81)
	23	Truck with new panel travels to bridge	7.31 (0.99)
	28	Install new panel	26.20 (1.89)
	31	New-panel truck returns to plant	5.31 (0.94)
	30	Team repositioning	17.69 (1.42)

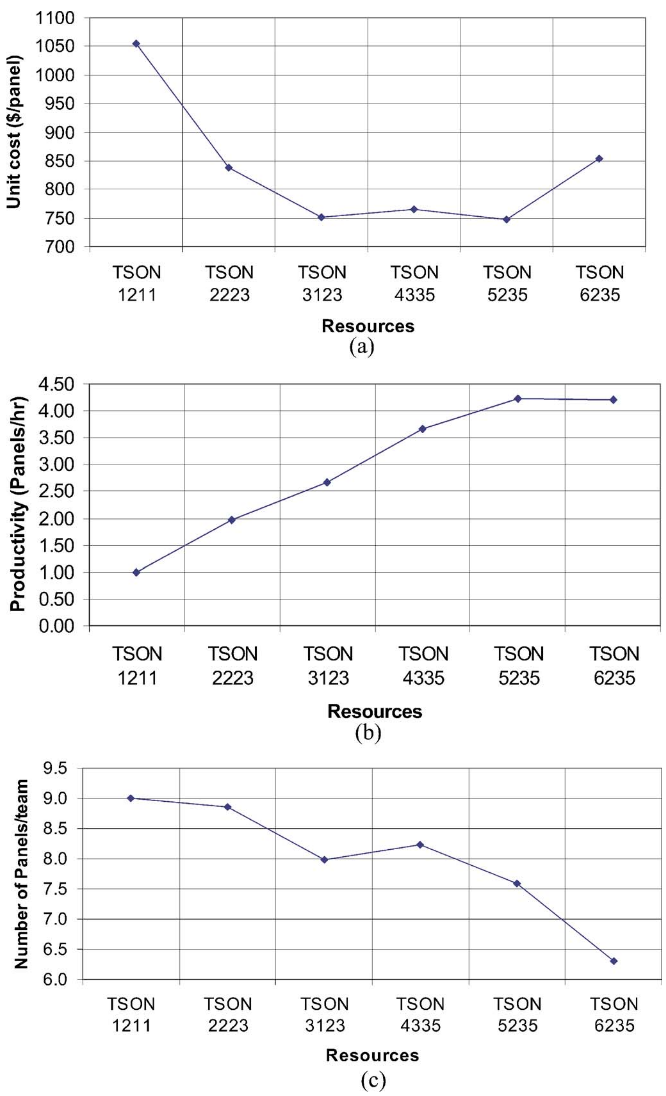

Fig. 6. Productivity and unit cost trends in different cases: (a) unit cost ($/panel); (b) productivity (panel/h); and (c) number of panels/team

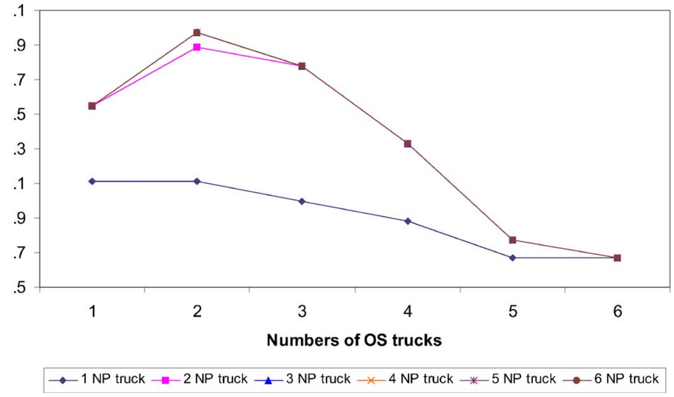

Fig. 7. Productivity analysis versus number of OS and NP trucks

Therefore, the maximum number of teams that can work simultaneously without conflict(s) is ten teams in accordance with the length of the bridge deck to be replaced, which is 600 m.

Sensitivity analysis is performed to select the optimum resource combination that generates higher productivity with lower expenses and conflicts. The following section introduces this analysis.

Sensitivity Analysis and Resource Optimization

The sensitivity analysis mentioned in this paper refers to a functionality provided by MicroCYCLONE, which allows the user to specify input, perform batches of simulation experiments, and obtain organized reports. The main objective of a simulation experiment is to optimize a given system's performance and learn more about its behavior. Some of the common optimization problems often encountered in planning (or controlling) a construction operation can be addressed using this model. Examples include optimal resource allocation within a construction operation to maximize hourly production, minimize the unit cost, or processing time of a job. In our case study, sensitivity analysis is applied to find the optimal resource combination for teams, saws, and trucks for carrying OS and NP. The generated number of combinations is 1296 ($6 \times 6 \times 6 \times 6$) to change the number of teams from one to six with one team increment; saws from one to six with one saw increment; OS trucks from one to six with one truck increment; and NP trucks from one to six with one truck increment. More combinations were tried to check the increase in productivity and decrease in cost. However, it is found that productivity does not increase beyond what was achieved using five teams when the number of teams was increased to seven, eight, nine, and ten.

The results of each combination are documented to select the optimal one based on further analysis. The combinations that have higher productivity and lower cost are selected because they dominate the other combinations that have similar or lower productivity and higher cost. However, a combination that has higher productivity and higher cost cannot be dominated. The index method that is developed by Zayed and Halpin (2001) is used to select the optimal combination among those that cannot be dominated. Fig. 6 shows the results of sensitivity analysis for the optimal combinations that have the lowest unit cost in terms of different teams. The "Case" column shows different combinations of teams, saws, OS trucks, and NP trucks. For example, "TSON: 1211" means the combination of one team, two saws, one OS

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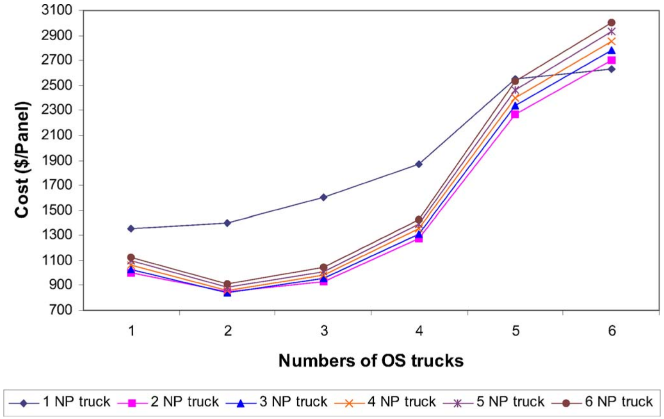

Fig. 8. Cost analysis versus number of OS and NP trucks

truck, and one NP truck. It is noticed that the lowest unit cost of all the combinations is $747, which involves five teams, two saws, three OS trucks, and five NP trucks.

Fig. 6 shows the trends of productivity and unit cost in different cases. It also shows the trend of the unit cost, panels per hour, and panels per team of the selected combination. The unit cost reaches the lowest value in the case of TSON: 5235. The productivity (number of panels per team) does not increase after the number of teams reaches five. Based on Fig. 6, the optimal combination of resources, which achieves maximum productivity and minimum cost, is five teams, two saws, three OS trucks, and five NP trucks.

It is noticed from Fig. 7 that productivity decreases with increasing number of OS and NP trucks. This decrease is steep when the number of NP trucks is above two but the slope is moderate in the case of only one NP truck. In all cases maximum production occurs when using two OS trucks and the number of NP trucks is higher than two. It is also noticed that the cost increases with the increase in the number of OS and NP trucks, as shown in Fig. 8. The lowest unit cost ($/panel) is for two OS trucks and three NP trucks. If one NP truck is used, the cost is higher; however, one OS truck has the lowest cost. Using one OS truck always generates higher cost than more OS trucks. On the other hand, Fig. 9 shows that the higher the number of teams, the higher the cost, except for two teams and one NP truck. It is obvious from this figure that using more than NP trucks is the cheapest decision.

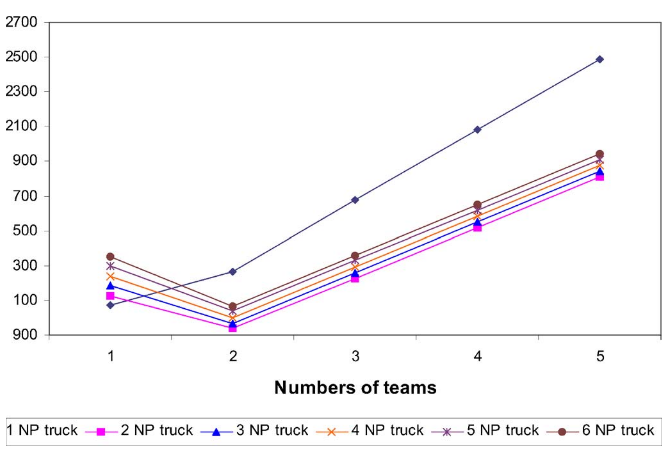

Fig. 9. Cost versus number of teams and NP trucks

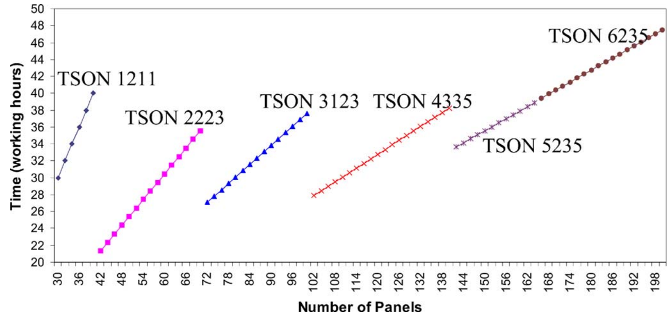

Fig. 10. Time versus number of panels in different cases

The results of the simulation can be used to optimize the resource allocation of bridge deck rehabilitation. Fig. 10 is developed to predict (based on the number of panels) the time required to accomplish the job and its associated resources. For projects similar to the Jacques Cartier Bridge redecking, the charts can be used as a conceptual cost estimate tool. For example, if a project similar to Jacques Cartier Bridge has 110 panels to be cut and installed, then the best resource combination is TSON: 4335 (four teams, three saws, three OS trucks, and five NP trucks). This project will take almost 30 working hours with a productivity of 3.66 panel/h/team. This number does not consider space conflicts, delays, or low production times. This job will cost approximately $83,000 (only direct cost), as shown in Fig. 11. The previous figures can be of great benefit to the estimator of a bridge redecking project and can be used as a rough estimation tool. In addition, these figures can also be helpful to bridge management agencies at the feasibility study stage. Furthermore, they can help contractors to manage their resources efficiently. For other project types, the approach or framework developed can be accommodated in order to build the simulation model. As such, several modifications are essential to activity durations and resource types and numbers. In addition, if the construction method is changed, the model developed has to be modified accordingly.

Model Test

The Jacques Cartier Bridge redecking case study project was constructed with different teams at different stages. At the beginning of the project, only one team was involved in the work, which resulted in an average of four panels per night. To improve pro-

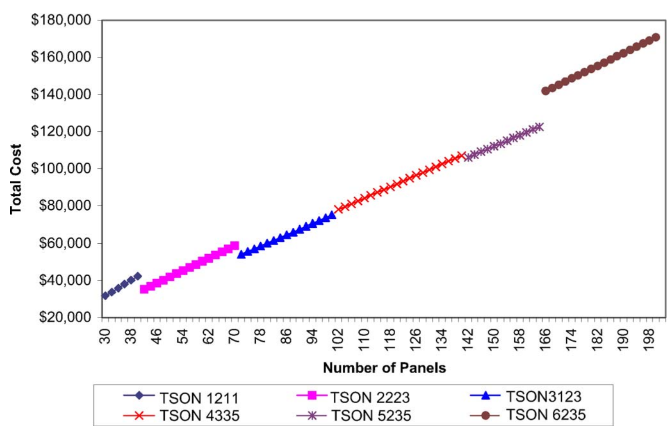

Fig. 11. Cost versus number of panels in different cases

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ductivity, another team was added to work at a different location on the bridge, which resulted in a total productivity of 12 panels per night. Because of bridge criticality, the contractor mobilized and demobilized equipment in 2–2.5 h daily. Therefore, the productivity time was approximately 5.5–6 h daily with a rate of 2–2.18 panels/h (actual productivity), as collected from the contractor. This productivity was performed using two teams, two saws, two trucks for carrying old sections, and three trucks for carrying new panels (TSON: 2223).

Based on Fig. 6(b) (generated from simulation model results), the productivity of such resource combination is 1.97 panel/h (predicted). By comparing both actual (2–2.18 panels/h) and predicted (1.97 panel/h), the model has 90.37–98.5% fitness. This value shows the potential of the approach developed in predicting deck rehabilitation productivity and optimizing contractor's resources in similar redecking projects. This approach can be utilized to plan future projects in order to maximize resource utilization and minimize expenses and user cost.

Conclusions

This research analyzed the possibility of finding an optimal combination of resources in bridge deck rehabilitation projects using discrete event simulation. A case study of a bridge redecking project (Jacques Cartier Bridge) was used to develop the simulation model. Probability distributions were fitted, which showed the robustness of the normal distribution in representing most variables. Simulation results showed that productivity is 0.89 panel/h if one team, one saw, one OS truck, and one NP truck are used. Sensitivity analysis results showed that the optimal resource combination to accomplish the redecking project is five teams, two saws, three OS trucks, and five NP trucks (TSON: 5235), which costs $747/h (in Canadian dollars) (direct cost only) for installing one panel. In addition, results showed that productivity decreases when increasing the number of OS and NP trucks. The present research also developed two charts to assess the time and resources required to accomplish a specific number of panels' replacement as well as their associated cost. The approach developed is 90.37–98.5% competent in solving the redecking resource management problem.

The present research is relevant to both academics and practitioners in which it provides a real case study, a simulation model, and an approach to analyze bridge redecking projects. It also provides practitioners with an approach to optimize the usage of their resources considering direct project cost.

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