Improving the Operational Efficiency of Post-Disaster Debris Hauling using Digital Twins

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BACKGROUND

Post-disaster debris removal is one of the most time-critical and costly components of disaster recovery, and delays in debris hauling can slow roadway clearance and reconstruction. Debris operations rely on repeated hauling cycles, travel to the debris pile, loading, hauling to a disposal site, dumping, and returning, which are influenced by congestion, travel distance, and equipment availability.

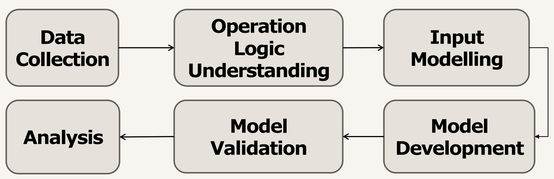
Problem Statement:

Existing debris collection operation are limiting in their ability to represent evolving real-world conditions during active recovery operations. Digital twin modeling provides a promising solution by replicating debris hauling cycles within a discrete-event simulation environment, allowing operations to be validated against observed data and supporting future optimization.

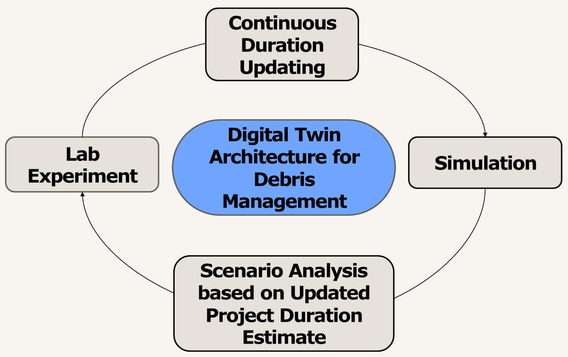
METHODOLOGY

Goal: To propose and validate the feasibility of a Digital Twin framework to improve the operational efficiency of post disaster debris collection using discrete event-based simulation.

Experiment Design:



Proposed Digital Twin Framework



Case Study:

Figure 1. Data Collection Setup

Table 1. Input Modelling Including Average Activity Durations

Activity	Average Simulation activity Durations (mins)	Observed Activity Durations (mins)
Park-to-pile	9.58	8.13
Load	11.05	12.19
Haul	13.06	12.85
Dump	4.99	4.89
Return-to-Pile	20.92	19.8
Dump-to-Park	20.74	20.74

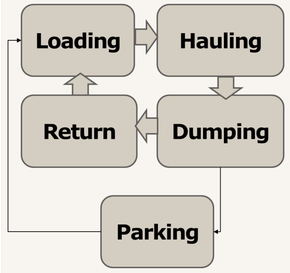
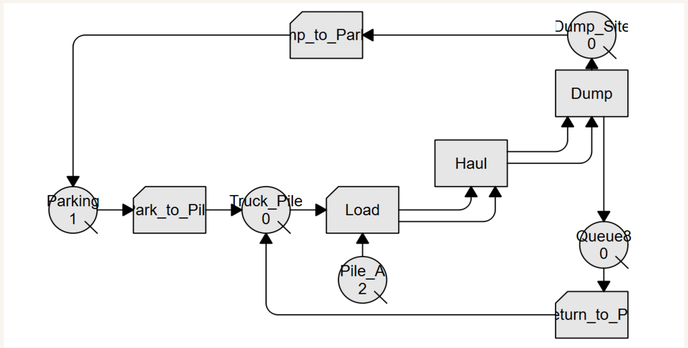


Figure 2. Process Logic

RESULTS



The debris hauling process was modeled using a discrete-event simulation representing the sequence of activities: park-to-pile, loading, hauling, dumping, and returning. Average activity durations obtained from observations were used as inputs to the model. Constrobe was used to develop the simulation model.

Model accuracy was evaluated by comparing simulated project duration estimates with observed project durations. The difference between these values was calculated using a loss function defined as the absolute error between simulated and observed durations.

Figure 3. Developed Simulation Model of the Post Disaster Debris Collection Operation

Simulation-based project duration estimation initially is not accurate but as we collect more data the estimations become more reliable.

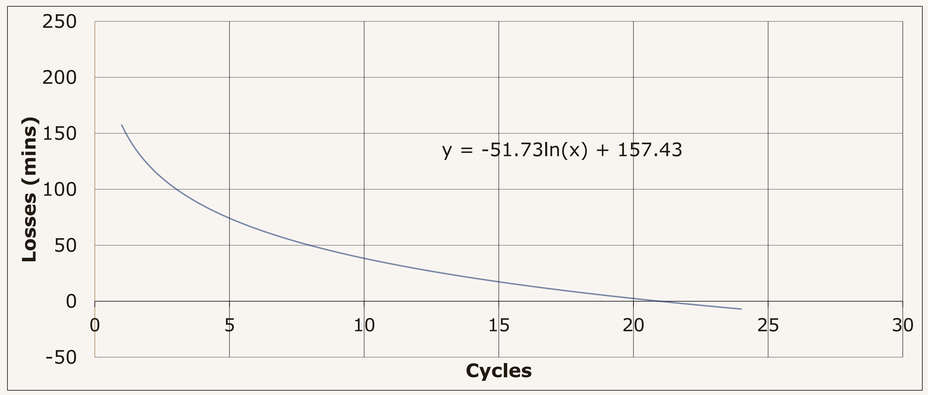


Figure 4. Loss Value Indicating the Difference Between Simulation and Observed Project Duration

Cycle	Loss
1	199.97
2	144.47
3	82.24
4	32.5
5	71.87
6	73.22
7	38.6
8	46.13
9	33.83
10	12.47
11	12.41
12	2.21
13	28.44
14	42.34
15	17.13
16	13.85
17	18.08
18	16.98
19	17.22
20	16.4
21	14.15
22	6.93
23	3.07
24	0

CONCLUSION

- This study proposed and validated a digital twin framework under deterministic assumptions within the lab environment using Discrete Event Simulation and manual updating of the parameters. The model was verified and validated to ensure alignment with real-world operation using test data.
- The incremental reduction of the loss at each update cycle indicated that the concept of digital twin can gradually increase the accuracy of initial estimates and reduce the uncertainty in estimation of recovery duration.

FUTURE WORK

- Integrate real-time data for continuous model updating.
- Expand to multiple trucks and congestion modeling.
- Incorporate routing, TDMS optimization, and the inclusion of sensors or automatic data collection.
- Apply model to full-scale disaster scenarios.

LIMITATIONS

- Assumes deterministic activity durations
- Assumes consistent operating conditions
- Does not yet include real-time updates
- Feasibility study under controlled environment

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REFERENCES

J. C. Martinez, "EZStrobe: General-Purpose Simulation System Based on Activity Cycle Diagrams," Proc. Winter Simulation Conf., 2001.

M. Nickdoost et al., "An Integrated Framework for Temporary Disaster Debris Management Site Selection and Debris Collection," Automation in Construction, 2022.

M. Batty, "Digital Twins," Environment and Planning B, 2018.