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Effects Of Workforce Productivity On Infrastructure Resilience

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Strategies to improve regional resilience rely on two key modeling components: predictive models for post-disaster infrastructure recovery and prescriptive models for logistics support. Predictive models encompass physical recovery modeling, coordinating geographically distributed recovery activities, and service recovery modeling, translating component recovery into spatially distributed infrastructure functionality. Prescriptive models involve problem formulation, identifying resilience objectives, decision variables, constraints, and computational algorithms for optimal solutions. While existing literature often employs linear programming and monetary objectives (González et al., 2016), Sharma et al., (2020) proposed a comprehensive approach, addressing specialized crews, scheduling constraints, and a multi-objective framework to separate resilience objectives from costs. However, these models overlook the human factor and atypical post-disaster conditions. Maintaining workers' well-being is crucial, considering the cognitive demands of recovery environments (Li et al., 2021). Previous research on human productivity has explored factors such as long work hours, sleep deprivation, shift structures, and the impact of rest (Van der Hulst, 2003; Dembe et al., 2006; Pencavel, 2015; 2016), yet no formulations guide decision-makers on optimal shift structures, crew composition, and time-cost tradeoffs. To achieve realistic modeling and optimization of regional resilience, it is imperative to integrate considerations for human performance in stressful environments, acknowledging the complex interplay of various physical and environmental conditions on productivity over time.

We propose an integrated model for infrastructure resilience enhancement that incorporates time-varying crew productivity in the recovery process. We develop the following integrated probabilistic formulation for time-varying human productivity:

$$\eta'_q = \omega_f(t)\,\omega\left(q_\kappa/q_{\kappa,\mathrm{min}}\right)^{1-\varepsilon_\kappa}\eta_q \tag{1}$$

Where η_q and η'_q are the base and the modified productivity values of a crew of type κ and size q_κ; $q_{\kappa,\mathrm{min}}$ is the minimum required crew size; ω is a factor that captures specific conditions such as weather (Sharma et al., 2018); ε_κ is a small positive constant to adjust for the crew congestion in a team, and $\omega_f(t)$ is the time-varying reduction factor due to fatigue. We estimate the predictive distribution $F\left[\omega_f(t_i)|h_w, T_s, d_r\right]$ where $\omega_f(t_i)$ is the fatigue reduction at any given time, based on the work hours per day h_w, daily shift start time T_s, and rest days per week d_r. We train the predictive model using data from Hursh et al., (2004) and Taoda et al., (2008). We then integrate the resulting model of time-varying productivity from Equation 1 with the formulation from Sharma et al., (2020) to develop a realistic model for the physical recovery of spatially distributed infrastructure. We also develop a computational approach that can provide stochastic optimization for physical recovery optimization and cost while also considering high-fidelity flow analysis.

We implemented the formulation for the resilience optimization of interdependent power and water infrastructure in Shelby County, Tennessee, USA, subject to a scenario earthquake. The infrastructure details and the earthquake scenario are available in Sharma et al., (2020). To study the impact of workforce productivity on resilience, we studied different work hours per day, h_w, rest days per week, d_r, and number of shifts in a day, s. Figures 1(a-b) are Pareto diagrams showing the results of the water infrastructure. Here, ρ_{physical} and ρ_{service} are resilience metrics (definitions available in Sharma et al., 2020) for physical recovery and recovery of functionality. Results indicate that work hours per day and rest days make a substantial difference to infrastructure resilience by affecting workforce productivity. We also observed that the effects worsened as the recovery times worsened. We found the proposed formulation effective in providing a monetary tradeoff of implementing rapid recovery using long working hours. Specifically for the case study, 16 work hours with two 8-hour shifts perform substantially better than the rest because it has twice the resources. Furthermore, shifts of 8, 10, and 12 work hours per day present a Pareto front at fixed resource levels.

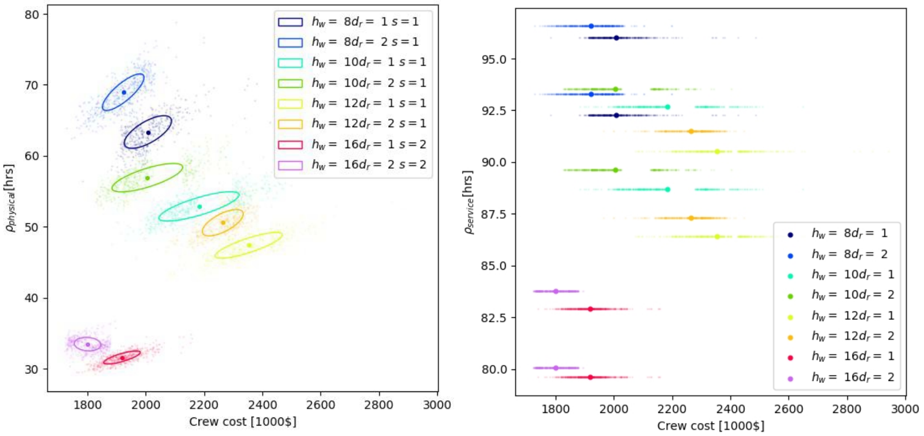

Fig. 1. Pareto diagrams for resilience and monetary cost objectives for the recovery of water infrastructure
(a) Physical resilience versus cost; (b) Functional resilience versus cost.

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