

Digital Twin for crisis logistics and intervention management under extreme conditions : State of the Art and Research Potential

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Abstract: A Digital Twin (DT) is an emerging decision-support tool that combines descriptive, predictive, and prescriptive modules to provide a comprehensive approach to complex decision-making. This capability makes it particularly relevant for addressing extreme weather events, which are becoming more frequent and intense due to climate change, often serving as major triggers of disasters. To explore the potential of DT in this context, we review existing literature on its applications and related technologies in crisis logistics and intervention management. Building on these insights, we propose a conceptual framework for applying DT to manage extreme weather events, detailing the technologies that support each component and demonstrating how DT can enhance disaster management strategies.

Keywords: Digital Twin, Extreme weather events, Extreme management situations

1. INTRODUCTION

In recent years, Digital Twins (DT) are emerging as new technologies to support decision-making processes in various fields of industry. A Digital Twin is designed to generate a virtual representation of a physical entity, with the purpose of enhancing and optimizing the entity's performance. It virtually evaluates and simulates different decisions, under real-world conditions and information, without affecting the physical entity (Semeraro et al., 2021). The concept of the Digital Twin was introduced in 2003 by Michael Grieves during a Product Lifecycle Management (PLM) course at the University of Michigan.

Digital twins (DT) enable the digital capture of physical assets, processes, or systems, allowing real-time interaction between the physical and digital worlds. To mirror the state of a physical asset, various data collection technologies such as Internet of Things (IoT) sensors, cameras, RFID, gather information from connected devices or objects. The data will be preprocessed and used as input for different models of the digital twin for further analysis and modeling. In the last decades, the advancements of new technologies of information and communication including Big data, Cloud computing, Internet of Things and Artificial Intelligence have boosted the development of digital twins in various fields.

Recently, the world have to face more and more frequent and intense extreme weather (events such as tropical storms, hurricanes, etc.) in the context of climate change. Recent works in the literature on the role of digital twins and related technologies in disaster management address several technical and organizational issues but remain mainly focused on the monitoring or prevision of emergency situations. Astarita et al., (2024) highlight a rise in publications on digital twins for mitigating natural disasters and extreme weather risks, from 2 in 2018 to 50 in 2023, reflecting growing interest in this tool for addressing climate change challenges. Most studies focus on enhancing urban resilience in smart cities (Fan et al., 2021, Ariyachandra & Wedawatta, 2023). Although, given that extreme weather is projected as the top long-term risk over the next decade (2024 World Economic Forum Report), we argue that digital twins could also play a valuable role to support decision making in disaster management.

Disaster management involves complex decision problems, including optimizing resource allocation, prioritizing evacuation strategies, selecting facility locations, and coordinating multi-agency responses

under uncertain conditions. Logistics systems are crucial to manage disasters but are vulnerable to disruptions caused by extreme weather events. In fact, those events, coupled with information chaos (Brandon, 2011), can lead to significant operational challenges, which may trigger extreme management situations. Those situations arise in environments characterized by high volatility, uncertainty, and risk (Lebraty, 2013), which require managers to make quick decisions based on limited available information. In such cases, conventional logistics management and decision support tools are inapplicable (Godé, 2015). It is therefore essential to develop new data-driven technologies, such as digital twins, which integrate real-time data, simulation, and optimization to support decision-making (Ivanov & Dolgui, 2021).

This paper focuses on the applications of Digital Twin in the management of extreme situations in the field of supply chain and logistics. The objective of this study is to address the following research questions:

- RQ1 : How to conceptualize an appropriate Digital Twin for the management of extreme situations due to extreme weather events ?
- RQ2 : How to structure a Digital Twin to facilitate decision-making support during extreme management situations ?

This paper is organized as follows. Section 2 is dedicated to a literature review on digital twins and related technologies in crisis logistics and emergency operations management. Section 3 presents key elements in design of digital twins for extreme management situations, before discussion and conclusion in sections 4 and 5.

2. LITERATURE REVIEW AND AREAS OF RESEARCH

According to (Alexander, 2002; Çelik et al., 2012), climate risk management can be approached cyclically in three phases:

- The pre-event phase consists of two stages: mitigation and preparedness. Mitigation aims to minimize the impact of future disasters through weather forecasting, building infrastructure and enhancing knowledge of extreme weather events. Preparedness focuses on actions to mitigate the effects of an imminent disaster by raising awareness among the population and preparing resources and safeguard measures.
- The during-event phase is characterized by the response measures. Emergency interventions led by state and local authorities aim at minimizing the number of casualties, reducing material damage, and stabilizing the exposed spread.
- The post-event phase involves recovery measures. Post-disaster management ensures a return to normal as quickly as possible, through debris collection and cleanup, damage repair, crisis logistics management and infrastructure reconstruction.

In this section, we examine the application of digital twins and related technologies to climate risk management, with a focus on crisis logistics and emergency operations management.

2.1 Research landscape in crisis logistics management

Crisis logistics management, an area related to the humanitarian supply chain organization, aims to provide the appropriate supplies at the right time to the affected population (Boostani et al., 2021). In crisis logistics, critical facilities such as shelters, distribution centers, warehouses or medical service centers are strategically placed to ensure the quick response to the population needs.

Few studies have explored the use of digital twins in improving the resilience of logistics systems. Brucherseifer et al., (2021) proposed a digital twin conceptual framework to improve critical infrastructure resilience.

Numerous studies focus on designing logistics systems using mathematical optimization. Gökçe & Ercan, (2019) explored a pre-disaster management initiative in Turkey involving reselling and replenishing emergency relief items stocked in containers. To address the challenge of managing items with expiration dates, the authors propose a mixed-integer programming model that optimizes replenishment policies and vehicle routing. The model aims to maximize total profit by balancing expected resale revenue with transportation and routing costs over a defined planning horizon. Cheng et al., (2021) developed an innovative robust goal programming model to insure equitable and effective distribution of food under uncertainties. Gao & Cao, (2020) present a bi-objective stochastic mixed-integer nonlinear programming problem, to effectively rebalance commodities among relief centers after disasters. The objective is to minimize transportation time and unmet demand in situations of traffic congestion and high demand uncertainty. Rezapour et al., (2021) propose a stochastic optimization model to identify the optimal timing for initiating stock prepositioning upon receiving a hurricane risk alert. The study evaluates trigger time based on two performance measures: total logistics cost and minimum response time for transferring goods.

2.2 *Research landscape in emergency operations management*

Emergency operations management in extreme conditions consists of planning, organizing, coordinating, and implementing emergency response activities in during- and post-event phases. It involves coordination among multiple actors such as local and national authorities, NGOs, international organizations, armed forces, and private sector entities. Hashemipour et al., (2018) presented a disaster multiagent coordination simulation system integrating machine learning, to help configure first-response teams before search and rescue operations. Hong & Shi, (2023) studied the collaborative management of heterogeneous sensors operated by public and private stakeholders in case of floods. The authors highlight the importance of managing diverse sensor systems and the role of metadata to enhance disaster response.

Several studies focused on optimization models and algorithms to improve decision support in emergency operations management. Rambha et al., (2021) present a stochastic optimization model designed to determine the evacuation order of hospital patients during hurricanes. Evacuating patients is risky due to the difficulty of providing care during transport, but remaining on-site can be dangerous due to flooding and power loss. The model prioritizes patient evacuations based on cost and risk trade-offs. Momeni et al., (2023) proposed a bi-objective mathematical optimization model to assist firefighters in determining the optimal number of trucks (serving as mobile drone depots) and drones required to access several hard-to-reach areas, while also minimizing the time and cost of operations.

3. CORE COMPONENTS OF DIGITAL TWINS FOR DISASTER MANAGEMENT

While responding to disasters, authorities face many uncertainties such as travel time variability, fluctuating demands, and capacity limitations (Barahona et al., 2013). Furthermore, the increasing frequency of simultaneous and overlapping disasters (Ba et al., 2021) underscores the critical need for effective collaboration between stakeholders.

In this context, we argue that digital twins could serve as a transformative cross-functional tool in disaster management. By aggregating data from diverse stakeholders (state and local authorities, NGO, meteorological organizations etc..) and enabling scenario simulations, digital twins can support informed decision-making, fostering enhanced collaboration and operational efficiency across all phases of disaster management.

The design of a digital twin for disaster management requires careful consideration of several parameters to prepare, respond and recover from risks. According to Eramo et al., (2021), a digital twin should consist of three components :

- *Descriptive component* represents historical and real-time data to offer a coherent picture of the disaster's progression, resource availability, and areas of critical need. Data visualized through tables, charts, diagrams or maps provide a clear overview of the situation to assess risks.

- *Predictive component* simulates "what-if" scenarios to anticipate risks and mitigate potential impacts on the real-world system. Methods such as discrete-event simulation, agent-based modeling, and system dynamics are typically utilized.
- *Prescriptive component* determine the best course of action by applying mathematical or computational optimization techniques. This component supports decision-makers in balancing cost, time, and effectiveness to ensure feasible, efficient responses that minimize harm and accelerate recovery in disaster management.

3.1 Conceptual Framework of Digital Twin for Extreme Weather Event Management

The proposed Digital Twin (Figure 1) is inspired by the frameworks of (Eramo et al., 2021; Ivanov & Dolgui, 2021). It integrates real-time and historical data collected from various organizations and stakeholders to provide a comprehensive, cross-functional perspective on the situation, leveraging disaster and logistics-related information.

This data serves as input to the Digital Twin’s modules. The *descriptive module* facilitates the visualization of extreme weather event propagation and the capacity constraints of multiple stakeholders. Subsequently, the data flows into the *predictive module*, which simulates high-impact, low-probability “what-if” scenarios. These simulations continuously evaluate risks across the four disaster phases: mitigation, preparedness, response, and recovery. The scenarios incorporate diverse parameters, including extreme event propagation, affected zones, and logistic capacity constraints. Finally, the scenarios are processed through a prescriptive model that encompasses multiple complex optimization problems, aiming to identify the fastest and most efficient solution that stakeholders can implement.

The digital twin serves a dual purpose: as a proactive decision-support system, it generates scenarios which helps optimize training for multiple response authorities during the mitigation and preparedness phases; and as a reactive decision-support system, it provides real-time alternative scenarios to assist stakeholders during the response and recovery phases.

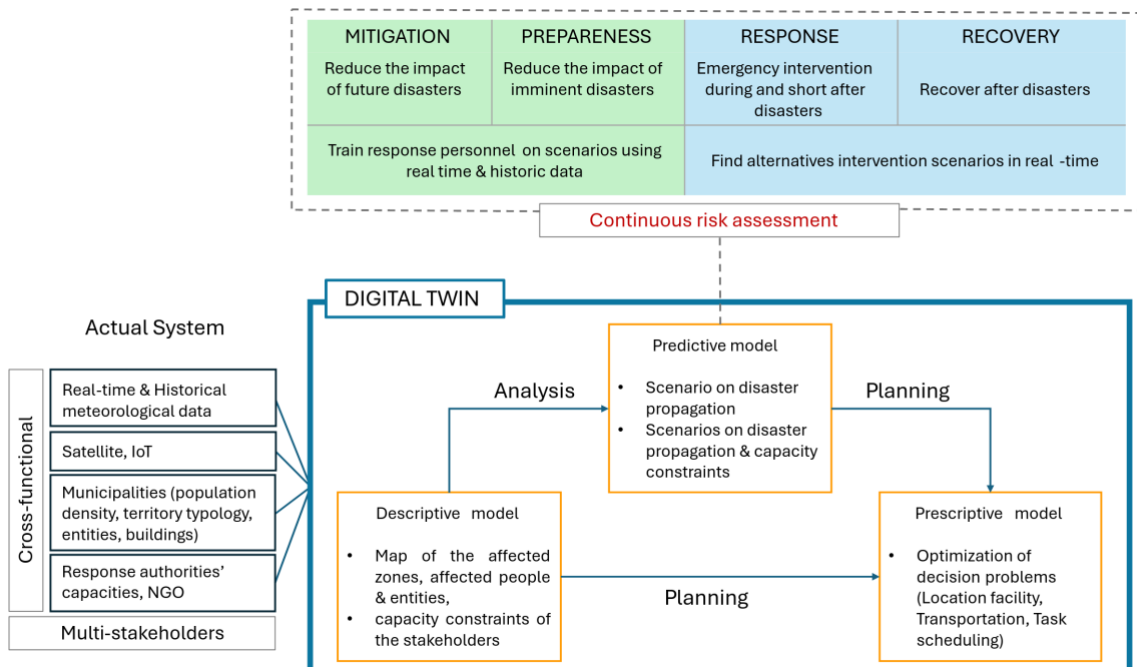


Figure 1 : Conceptual Framework of Digital Twin for Extreme Weather Event Management

The technologies used in the descriptive, predictive and prescriptive components are described in the following sections.

3.1 Technologies for data collection and processing

In the descriptive component, a Geographic Information System (GIS) could be used to map extreme weather events in order to assess risks, identify vulnerabilities, and visualize shelter locations (Ortiz, 2020). Lourenço et al., (2021) focuses on wildfire mapping in Macau, Portugal using a Spatial Decision Support System (SDSS) based on ArcGIS Online to collect data from multiple sources in real time, enabling the geolocation and analysis of firefighters' environment in the field (oxygen levels, humidity, temperature, etc.). Similarly, Balogun et al., (2018) propose the creation of Environmental Sensitivity Risk Maps to identify marine species at risk during oil spills, ensuring effective intervention by stakeholders.

The data visualized in those maps can be collected thanks to the Internet of Things (IoT). Pre-disaster IoT systems focus on predicting potential disasters using strategically placed sensors, while post-disaster systems improve the effectiveness of evacuation, relief efforts, and victim tracking. Bail et al., (2021) categorize the applications of IoT in disaster management as follows: enabling real-time disaster detection, facilitating emergency response and victim tracking, and monitoring transport vehicles and emergency supply.

Successful implementation of IoT in disaster management requires addressing other factors, such as artificial intelligence for data analysis and predictive modeling, or big data and cloud computing for scalable data storage and processing.

Big Data technologies refer to the large and complex datasets generated by digital devices, sensors, social media, transactional systems, and more. Big Data can be combined with analytics processes by employing advanced mathematical, statistical, probabilistic, or artificial intelligence models to uncover patterns, trends, and insights that would be difficult to detect with traditional data-processing tools (Rathore et al., 2021).

Data processing techniques including the use of artificial intelligence and machine learning for statistical and uncertainty analysis have a crucial impact on the implementation of digital twins for disaster risks management. It significantly improves the accuracy and reliability of data, particularly in situations where the intricate nature of disaster scenarios complexifies disaster risk data processing (Lagap & Ghaffarian, 2024). Sun et al., (2020) found that the number of publications about disaster management and artificial intelligence increased significantly since 2007. The authors explain that AI can be used in all phases of disaster management to analyze large amounts of data in order to assess risks and vulnerability.

3.2. Simulation

Simulation is the process of creating a model that replicates the behavior of a system allowing for virtual testing and experimentation without incurring the risks or costs associated with directly interacting with the actual system.

In disaster risk management, simulation models are crucial to design various disaster scenarios in order to understand the potential impacts on communities, infrastructure, and ecosystems. They help assess the risks associated with different hazards, considering factors like vulnerability, exposure, and potential loss. The models can incorporate various data sources to evaluate real world scenarios with historical data of past events. Such data include the nature of extreme events, information provided by municipalities (population density, territory typology, building types etc.), historical incident data (Iglesias et al., 2024), historical and forecasted weather as well as emergency response capabilities. The solutions obtained from the different approaches tested across the scenarios are compared using various perspectives including quality and flexibility. Simulations enable emergency responders to practice their roles in a controlled environment for training exercises.

The simulation can be used in conjunction with other technologies to enhance decision-making and training processes in disaster risk management. Artificial intelligence improves simulation models in disaster risk management. Chamola et al., (2021) classified Machine Learning algorithms in the context of managing extreme events. Convolutional Neural Network models and Random Forest classifiers are

often used for flood prediction. For instance, the latter was employed to predict the occurrence of storms and precipitation between 2015 and 2021 in the 947 municipalities of Catalonia (Iglesias et al., 2024).

3.3 *Optimization problems and solution techniques*

Optimization problems in disaster risk management involve finding the most efficient and effective solutions for decision-making support in emergency situations to minimize the impact of disasters on human lives, economic assets and the environment. These decision problems are often complex and require balancing multiple objectives such as cost, time, safety, and resource allocation under dynamic and extreme environmental conditions. Çelik et al., (2012) conducted a literature review to categorize the OR/MS topics addressed in each of the four phases of disaster management. Their findings reveal that most papers focus on facility location, supply distribution, inventory management, transportation, and operational flow.

Location problems are a class of optimization problems that determine the optimal placement of facilities or resources to minimize transportation and structure costs, maximize efficiency, or improve service while taking into account different constraints. Location problems under disaster conditions contribute to improve the relief process for affected population by identifying the optimal strategic location of distribution centers, warehouses, shelters, medical service centers, or even blood donation centers (Madani Saatchi et al., 2021; Seraji et al., 2022; Nayeri et al., 2023).

Routing problems are a category of optimization challenges that involve determining the most efficient tours for delivering goods, services or transporting people within a network, while minimizing the transportation cost or time. In emergency situations, those problems are applied to optimize the movement of emergency services (ambulances, fire trucks, etc.), supplies (medical supplies, food, water, etc.), and personnel (evacuation, etc.) (Anuar et al., 2021; Lu et al., 2022; Masoumi et al., 2021; Shahparvari et al., 2019).

Scheduling problems are related to the allocation of resources (machines, teams, tec.) to complete a set of activities within specified constraints in the minimum completion time. In disaster management, those problems are crucial to schedule shifts for relief workers, determining the timing and sequencing of supply distribution, or coordinating the use of limited equipment and facilities (Rottondi et al., 2021; Tippong et al., 2022; Li et al., 2024).

Complex optimization problem solving requires the use of advanced mathematical models, sophisticated algorithms, and computational resources to explore efficiently large solution spaces. It also demands careful consideration of constraints, trade-offs between multiple objectives, and the ability to handle uncertainty or incomplete information. Mathematical models, heuristic/metaheuristic algorithms with local search procedures (Houssein et al., 2021; Abualigah et al., 2023) as well as machine learning and reinforcement learning algorithms could be used. One of the main challenges in this research field is to train a model within sufficiently small samples that enables the policy to fully utilize the problem's structure to generate better results (Bengio et al., 2021; Grinsztajn et al., 2023).

4. DISCUSSION

Disaster management relies on mitigating risks through effective information sharing, collaboration, and coordinated actions by public and private authorities. Similar to logistics and supply chain management (SCM), it requires optimizing warehouse networks, designing accessible distribution systems, predicting inventory needs, and coordinating stakeholders' operations. These efforts must balance critical constraints such as cost, time and demand satisfaction.

Humanitarian supply chains are vulnerable to disruptions from external hazards such as natural disasters and extreme weather events, creating volatile, uncertain, and high-risk environments. Such scenarios can lead to extreme management situations where managers must make quick decisions in high stress conditions, often relying on incomplete information. In such cases, conventional logistics management and decision support tools are inapplicable.

While Digital Twins have been extensively studied in Supply Chain Management, particularly since the COVID-19 pandemic as a tool to enhance resilience (Ivanov & Dolgui, 2021; Lam et al., 2023), its application to disaster management remains an emerging research field.

There is considerable potential for future research on the integration of Digital Twins into crisis logistics, for organizations to achieve faster, more efficient, and more adaptive disaster response operations, ultimately saving lives and ensuring that aid reaches those in need in a timely and effective manner. Only few studies focus on DT for crisis logistics in the literature. There is a clear need for research focusing on the convergence of new technologies and DT incorporating optimization models for disaster management.

Our proposed framework addresses this gap, focusing on extreme weather events due to climate change. However, the framework faces a limitation: its reliance on data collected from multiple sources, a process that can be complex and resource intensive. To address this challenge, further research and stakeholder engagement are needed to identify the critical data types required for effective risk assessment and decision-making.

5. CONCLUSION

In this paper, we are interested in the application of digital twins in the management of extreme situations in the field of supply chain and logistics. A literature review is conducted to provide a comprehensive overview of the field. We then propose a conceptual Digital Twin framework integrating visualization, simulation, and optimization modules to aid decision-making across all phases of disaster management: mitigation, preparedness, response, and recovery. By leveraging technologies for data integration, scenario simulation, and optimization, the proposed DT framework offers a structured approach to facilitate coordination, resource allocation, and operational efficiency during extreme situations. Future research could focus on addressing the challenges of data collection and integration from multiple sources, which are critical to implementing the proposed framework. Another interesting research track could focus on exploring the potential of new machine learning and optimization approaches to enhance the effectiveness and reliability of analytics for decision-making under uncertainty.

REFERENCES

- Abualigah, L., Hanandeh, E. S., Zitar, R. A., Thanh, C.-L., Khatir, S., & Gandomi, A. H. (2023). Revolutionizing sustainable supply chain management: A review of metaheuristics. *Engineering Applications of Artificial Intelligence*, 126, 106839.
- Alexander, D. (2002). *Principles of Emergency Planning and Management* (1st edition). Oxford University Press.
- Anuar, W. K., Lee, L. S., Pickl, S., & Seow, H.-V. (2021). Vehicle Routing Optimisation in Humanitarian Operations: A Survey on Modelling and Optimisation Approaches. *Applied Sciences*, 11(2), 667.
- Ariyachandra, M. R. M. F., & Wedawatta, G. (2023). Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts. *Sustainability*, 15(15), 11910.
- Astarita, V., Guido, G., Haghshenas, S. S., & Haghshenas, S. S. (2024). Risk Reduction in Transportation Systems: The Role of Digital Twins According to a Bibliometric-Based Literature Review. *Sustainability*, 16(8), 3212.
- Ba, R., Deng, Q., Liu, Y., Yang, R., & Zhang, H. (2021). Multi-hazard disaster scenario method and emergency management for urban resilience by integrating experiment–simulation–field data. *Journal of Safety Science and Resilience*, 2(2), 77–89.
- Bail, R. D. F., Kovaleski, J. L., Da Silva, V. L., Pagani, R. N., & Chiroli, D. M. D. G. (2021). Internet of things in disaster management: Technologies and uses. *Environmental Hazards*, 20(5), 493–513.
- Balogun, A.-L., Matori, A., & Kiak, K. (2018). DEVELOPING AN EMERGENCY RESPONSE MODEL FOR OFFSHORE OIL SPILL DISASTER MANAGEMENT USING SPATIAL DECISION SUPPORT SYSTEM (SDSS). *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-3, 21–27.

- Barahona, F., Ettl, M., Petrik, M., & Rimshnick, P. M. (2013). Agile logistics simulation and optimization for managing disaster responses. *2013 Winter Simulations Conference (WSC)*, 3340–3351.
- Bengio, Y., Lodi, A., & Prouvost, A. (2021). Machine learning for combinatorial optimization: A methodological tour d’horizon. *European Journal of Operational Research*, 290(2), 405–421.
- Boostani, A., Jolai, F., & Bozorgi-Amiri, A. (2021). Designing a sustainable humanitarian relief logistics model in pre- and postdisaster management. *International Journal of Sustainable Transportation*, 15(8), 604–620.
- Brandon, P. S. (2011). Extreme Management in Disaster Recovery. *Procedia Engineering*, 14, 84–94.
- Brucherseifer, E., Winter, H., Mentges, A., Mühlhäuser, M., & Hellmann, M. (2021). Digital Twin conceptual framework for improving critical infrastructure resilience. *At - Automatisierungstechnik*, 69(12), 1062–1080.
- Çelik, M., Ergun, Ö., Johnson, B., Keskinocak, P., Lorca, Á., Pekgün, P., & Swann, J. (2012). Humanitarian Logistics. In *2012 TutORials in Operations Research* (pp. 18–49). INFORMS.
- Chamola, V., Hassija, V., Gupta, S., Goyal, A., Guizani, M., & Sikdar, B. (2021). Disaster and Pandemic Management Using Machine Learning: A Survey. *IEEE Internet of Things Journal*, 8(21), 16047–16071.
- Cheng, J., Feng, X., & Bai, X. (2021). Modeling equitable and effective distribution problem in humanitarian relief logistics by robust goal programming. *Computers & Industrial Engineering*, 155, 107183.
- Eramo, R., Bordeleau, F., Combemale, B., Brand, M., Wimmer, M., & Wortmann, A. (2021). Conceptualizing Digital Twins. *IEEE Software*, PP.
- Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management*, 56, 102049.
- Gao, X., & Cao, C. (2020). Multi-commodity rebalancing and transportation planning considering traffic congestion and uncertainties in disaster response. *Computers & Industrial Engineering*, 149, 106782.
- Godé, C. (2015). *La coordination des équipes en environnement extrême*.
- Gökçe, M. A., & Ercan, E. (2019). Multi-Period Vehicle Routing & Replenishment Problem of Neighbourhood Disaster Stations for Pre-Disaster Humanitarian Relief Logistics. *IFAC-PapersOnLine*, 52(13), 2614–2619.
- Grinsztajn, N., Furelos-Blanco, D., Surana, S., Bonnet, C., & Barrett, T. D. (2023). *Winner Takes It All: Training Performant RL Populations for Combinatorial Optimization* (arXiv:2210.03475).
- Hashemipour, M., Stuban, S., & Dever, J. (2018). A disaster multiagent coordination simulation system to evaluate the design of a first-response team. *Systems Engineering*, 21(4), 322–344.
- Hong, J.-H., & Shi, Y.-T. (2023). Integration of Heterogeneous Sensor Systems for Disaster Responses in Smart Cities: Flooding as an Example. *ISPRS International Journal of Geo-Information*, 12(7), 279.
- Houssein, E. H., Mahdy, M. A., Shebl, D., & Mohamed, W. M. (2021). A Survey of Metaheuristic Algorithms for Solving Optimization Problems. In D. Oliva, E. H. Houssein, & S. Hinojosa (Eds.), *Metaheuristics in Machine Learning: Theory and Applications* (pp. 515–543). Springer International Publishing.
- Iglesias, J., Cuesta, I., Salueña, C., Solé, J., Prevatt, D. O., & Fabregat, A. (2024). Predictive modeling of severe weather impact on individuals and populations using Machine Learning. *International Journal of Disaster Risk Reduction*, 105, 104398.
- Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control*, 32(9), 775–788.
- Kwok, P. K., Yan, M., Chan, B. K. P., & Lau, H. Y. K. (2019). Crisis management training using discrete-event simulation and virtual reality techniques. *Computers & Industrial Engineering*, 135, 711–722.
- Lagap, U., & Ghaffarian, S. (2024). Digital post-disaster risk management twinning: A review and improved conceptual framework. *International Journal of Disaster Risk Reduction*, 110, 104629.
- Lam, W. S., Lam, W. H., & Lee, P. F. (2023). A Bibliometric Analysis of Digital Twin in the Supply Chain. *Mathematics*, 11(15), 3350.
- Lebraty, J.-F. (2013). SI et situations extrêmes. *Systèmes d’information & management*, 18(1), 3–10.

- Li, Z., Yan, J., & Xue, J. (2024). Multi-objective fuzzy surgical scheduling during post-disaster with Nash equilibrium. *Expert Syst. Appl.*, 238(PC).
- Lourenço, M., Oliveira, L. B., Oliveira, J. P., Mora, A., Oliveira, H., & Santos, R. (2021). An Integrated Decision Support System for Improving Wildfire Suppression Management. *ISPRS International Journal of Geo-Information*, 10(8), 497.
- Lu, Y., Yang, C., & Yang, J. (2022). A multi-objective humanitarian pickup and delivery vehicle routing problem with drones. *Annals of Operations Research*, 319(1), 291–353.
- Madani Saatchi, H., Arshadi Khamseh, A., & Tavakkoli-Moghaddam, R. (2021). Solving a new bi-objective model for relief logistics in a humanitarian supply chain by bi-objective meta-heuristic algorithms. *Scientia Iranica*, 28(5), 2948–2971.
- Masoumi, M., Aghsami, A., Alipour-Vaezi, M., Jolai, F., & Esmailifar, B. (2021). An M/M/C/K queueing system in an inventory routing problem considering congestion and response time for post-disaster humanitarian relief: A case study. *Journal of Humanitarian Logistics and Supply Chain Management*, 12(2), 182–219.
- Momeni, M., Soleimani, H., Shahparvari, S., & Afshar-Nadjafi, B. (2023). A multi-agency coordination resource allocation and routing decision-making problem: A coordinated truck-and-drone DSS for improved wildfire detection coverage. *International Journal of Disaster Risk Reduction*, 97, 104027.
- Nayeri, S., Khoei, M. A., Rouhani-Tazangi, M. R., GhanavatiNejad, M., Rahmani, M., & Tirkolaee, E. B. (2023). A data-driven model for sustainable and resilient supplier selection and order allocation problem in a responsive supply chain: A case study of healthcare system. *Engineering Applications of Artificial Intelligence*, 124, 106511.
- Ortiz, D. (2020). *Geographic Information Systems (GIS) in Humanitarian Assistance: A Meta-Analysis*.
- Rambha, T., Nozick, L. K., Davidson, R., Yi, W., & Yang, K. (2021). A stochastic optimization model for staged hospital evacuation during hurricanes. *Transportation Research Part E: Logistics and Transportation Review*, 151, 102321.
- Rathore, M. M., Shah, S. A., Shukla, D., Bentafat, E., & Bakiras, S. (2021). The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities. *IEEE Access*, 9, 32030–32052. IEEE Access.
- Rezapour, S., Farahani, R. Z., & Tajik, N. (2021). Impact of timing in post-warning prepositioning decisions on performance measures of disaster management: A real-life application. *European Journal of Operational Research*, 293(1), 312–335.
- Rottondi, C., Malandrino, F., Bianco, A., Chiasserini, C. F., & Stavrakakis, I. (2021). Scheduling of emergency tasks for multiservice UAVs in post-disaster scenarios. *Computer Networks*, 184, 107644.
- Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry*, 130, 103469.
- Seraji, H., Tavakkoli-Moghaddam, R., Asian, S., & Kaur, H. (2022). An integrative location-allocation model for humanitarian logistics with distributive injustice and dissatisfaction under uncertainty. *Annals of Operations Research*, 319(1), 211–257.
- Shahparvari, S., Abbasi, B., Chhetri, P., & Abareshi, A. (2019). Fleet routing and scheduling in bushfire emergency evacuation: A regional case study of the Black Saturday bushfires in Australia. *Transportation Research Part D: Transport and Environment*, 67, 703–722.
- Sun, W., Bocchini, P., & Davison, B. D. (2020). Applications of artificial intelligence for disaster management. *Natural Hazards*, 103(3), 2631–2689.
- Tippong, D., Petrovic, S., & Akbari, V. (2022). A review of applications of operational research in healthcare coordination in disaster management. *European Journal of Operational Research*, 301(1), 1–17.