95 Ontology-Based Semantic Modeling of Disaster Resilient Construction Operations: Towards a Knowledge-Based Decision Support System

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Abstract

Construction sites are dynamic and complex; they are the most vulnerable environments to natural disasters such as hurricanes. Wind-caused damage to the construction sites could cause millions of dollar losses, considerable schedule delays, and threats to both worker safety and public safety. Therefore, there is sorely a need to enhance the overall resilience of construction projects and implement resilient construction operations. However, there is a lack of research that focuses on enhancing the resilience of construction operations during the construction phase as most existing research focuses on enhancing the structural resilience of the completed buildings or infrastructures. There is a lack of holistic and systematic knowledge that ensures whole life-cycle disaster management of construction projects. To address the gap, this paper aims to develop an ontology-based semantic model of disaster resilient construction operations to formally represent and reason about the knowledge of resilient construction operations during wind disasters. This paper starts by presenting the research method, and it follows by presenting our initial modeling and validation efforts towards a formal semantic model on disaster resilient construction operations. Finally, the paper discusses our proposed framework for a knowledge-based decision support system that allows for knowledge access, classification, and transfer on disaster resilient construction operations. The model, together with its potential application of the knowledge-based system would allow construction professionals to share and transfer domain-specific knowledge on construction disaster resilience, which will eventually contribute to enhance the whole life-cycle disaster resilience of construction projects.

Keywords

Ontology • Semantic model • Disaster resilient construction operation • Disaster resilience • Knowledge management • Decision support system

95.1 Introduction

Disasters, either natural or man-made, are responsible for approximate 57 billion annual cost in the U.S., in terms of injuries and life cost, property destruction, emergency services, etc. [11, 15]. Construction sites, comparing to completed infrastructures and buildings, are more vulnerable to disasters as they include incomplete structures and unsecured materials and equipment. They are the most vulnerable environments to natural disasters such as hurricanes [1]. In addition to the wind-caused property damage to the construction sites, disasters could cause significant schedule delays, millions of dollar losses, and they also threaten the safety of both the construction workers and the public. For example, during Hurricane Irma,

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three construction cranes at South Florida construction sites bent and collapsed, which caused severe losses to the projects and posed major threats to the public safety [18]. Therefore, there is sorely a need to enhance the overall resilience of the construction sites as well as construction operations before, during and after disasters.

Despite the evident needs of enhancing construction resilience, there are several theoretical and practical gaps that remain unresolved. First, there is a lack of research that primarily focuses on enhancing the resilience of construction operations during the construction phase. Although there is an abundant of existing research (e.g., [7–9, 20]) in the areas of resilient buildings and infrastructures, most of this research focuses on enhancing the resilience of completed buildings or infrastructures. For example, Cerè et al. [8] focused on analyzing the effects of geo-hazards and enhancing the resilience of the structures of completed buildings. Campanella [7] focused on the practices during the disaster preparedness phase for enhancing the resilience of urban infrastructures to minimize the loss of life. Thus, most of the studies on disaster resilience, especially hurricane disaster resilience, have been limited to completed buildings or infrastructures, and less attention has been paid on how hurricanes could damage the vulnerable construction sites and their surrounding environments. Second, the existing practices and safety rules for the construction operations (e.g., [16, 17]) are limited in supporting overall disaster resilience as they include the general plans that primarily focus on the mitigation and preparedness phases of disaster management such as transporting building materials and equipment to a safe place, bracing equipment and structures at the hurricane warning phase. Therefore, there is a lack of holistic and systematic knowledge before, during and after the disasters that ensures whole life-cycle disaster management of construction projects.

To fill these gaps, we aim to propose an ontology-based semantic knowledge-based decision support system (DSS) that allows for the access, classification, and transfer of knowledge on disaster resilient construction operations (DRCOs). As the first step of the work, this paper focuses on discussing our proposed ontology-based semantic model of DRCOs to formally represent and reason about the knowledge of DRCOs. The model serves as the foundation for developing the semantic knowledge-based DSS. This paper presents our initial modeling and validation efforts towards a formal semantic model on DRCOs. It also discusses our proposed framework for the knowledge-based DSS.

95.2 Methodology

We benchmarked and adapted the methodology of ontology development by El-Gohary and El-Diraby [10]. First, the domain, purpose, potentials users, and scope of the proposed semantic model of disaster resilient construction operations (DRCOs-Onto) were defined. Second, a set of competency questions (CQs) were developed for which the semantic model should be able to answer [10, 12]. These questions were used to formulate and evaluate the DRCOs-Onto. Three main types of CQs were developed: (1) inheritance CQs that define “is-a” relationships between concepts (e.g., what are the sub-concepts of a DRCO?) (2) modality CQs that define DRCO modalities and modality families (e.g., is incomplete structural integrity enhancement a physical resilient operation?) (3) relational CQs that define relationships between concepts (e.g., who is involved in a DRCO)? Third, the taxonomy (concept hierarchy) was built through two main iterative steps: (1) extraction and identification of the main concepts of the domain and (2) organization of these main concepts into a hierarchical taxonomy. The concepts of the domain were extracted based on the review of the specific literature about the construction process, operations, and disaster resilience in construction (e.g., [3, 5, 11, 13, 19, 21, 22]). Fourth, the ontology model was evaluated by checking conformance with CQs. We will also conduct expert interviews and application-oriented evaluation to evaluate the representation, coverage, consistency, clarity, conciseness, extendibility, and applicability of the DRCOs-Onto as part of our future work.

95.3 Main DRCOs-Onto Model

The DRCOs-Onto is composed of concepts, relations between the concepts, and axioms. Concepts represent the “things” that describe the process of DRCOs. Relations define the interactions between the different concepts. Axioms specify the definitions of concepts and relations, they also define the rules and requirements for DRCOs.

The upper-level model, which shows the most abstract concepts of the model, is depicted in Fig. 95.1. As per Fig. 95.1, the DRCOs-Onto has the following main concepts: disaster resilience technique operation, actor, resource, disaster resilient technique, constraint, disaster resilience objective, disaster resilient outcome, and context.

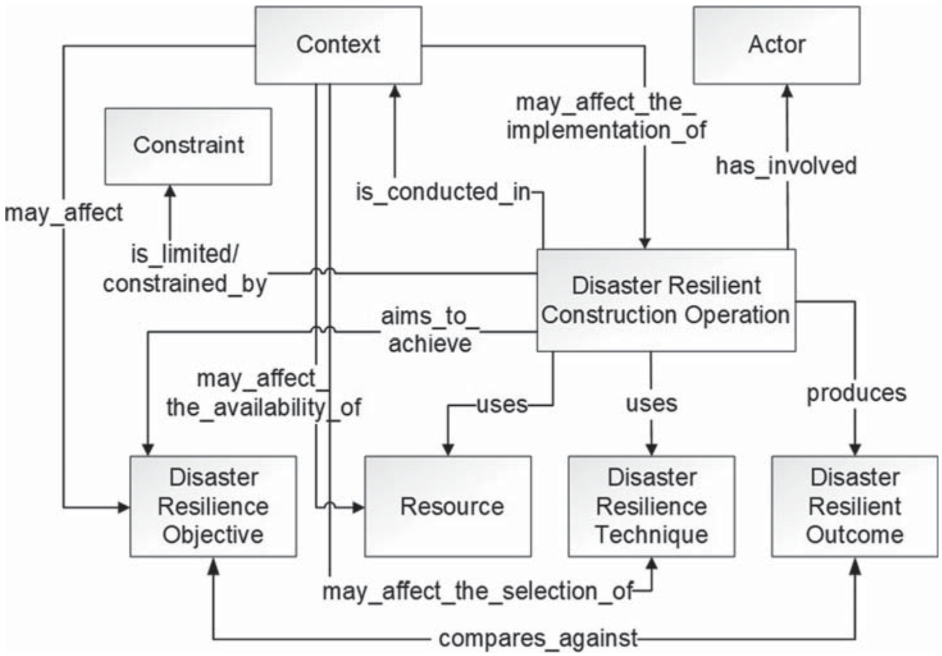

Fig. 95.1 Main DRCOs-Onto model

A "disaster resilient construction operation" has an "actor" involved. An "actor" is the personnel that plays a role in disaster resilient construction, such as a superintendent, a field engineer, an emergency personnel, etc. A "disaster resilient construction operation" aims to achieve a "disaster resilience objective" using a "resource" and a "disaster resilience technique". A "resource" is defined as the source and supply of the required items for a DRCO to obtain a disaster resilient outcome. It is a physical resource (e.g., material, equipment, human resource), a financial resource (e.g., budget of the project), and a knowledge item (e.g., construction schedule report). A "disaster resilience technique" is defined as a method or a technique that operates a DRCO, and it is a disaster resilience guideline (e.g., risk mitigation strategy), a disaster resilience method (e.g., risk management technique), and a disaster resilience measure (e.g., impact test, ductility test). A "disaster resilient construction operation" aims to achieve a "disaster resilience objective", and it produces a "disaster resilient outcome". A "disaster resilience objective" is a specific goal that a DRCO aims to achieve, such as generating knowledge of construction disaster resilience or building a disaster resilient structures; while a "disaster resilient outcome" is a consequence or an effect of implementing a DRCO. A "disaster resilient construction operation" is limited or constrained by a "constraint". A "constraint" is a specific condition that limits a DRCO. It is either an internal constraint (e.g., project budget, project specification, stakeholder's requirement) or an external constraint (e.g., engineering practice, regulatory body, work environment condition). A "disaster resilient construction operation" is conducted in a "context". A "context" is a set conditions, circumstances or parameters that affects or has an influence on a DRCO. A "context" may affect the implementation of a "disaster resilient construction operation". For example, the location of a residential building project (e.g., in Miami) may affect the selection of construction materials (e.g., concrete blocks, high strength masonry cement) that can withstand the category five hurricanes.

95.4 Disaster Resilience Concept Hierarchy

As a preliminary effort in developing the DRCOs-Onto, in this paper, we focus on presenting the concept hierarchy for DRCOs. The concept of DRCO was classified according to the different modalities to support polymorphic views of the same concept. Modality is used to define the belonging criteria of a concept to a family [10]. For example, "incomplete structure integrity enhancement" can be viewed as a "physical resilient operation", a "robust operation", and a "disaster mitigation operation" depending on the perspectives of construction operation impact, resilience characteristic, or disaster management cycle.

95.4.1 Construction Operation Impact Modality View

In the DRCOs-Onto, the main modality view is the construction operation impact modality view (as shown in Fig. 95.2). Construction operations have an impact on or change human society in different dimensions, such as the physical buildings or infrastructures, the society, the economy, and the environments. Therefore, a DRCO can be classified as a "physical resilient operation", a "social resilient operation", an "economic resilient operation", or an "environmental resilient operation". By benchmarking the literatures in the disaster resilience domain (e.g., [2, 6, 19, 22]), the definitions of the sub-level concepts are described below.

For physical resilient operations, six sub-level concepts were defined:

(1) Integrity enhancement is an operation that enhances the ability of either an under-construction structure (i.e., incomplete structure) or an equipment to support a designed load without breaking during the disasters.
(2) Quality control is an operation that aims to ensure the appropriate use of disaster-resistant materials and equipment to support disaster resilience.
(3) Resource management is a process that ensures the availability of labor/manpower, equipment, and materials and utilizes them in the most effective way during the disasters.

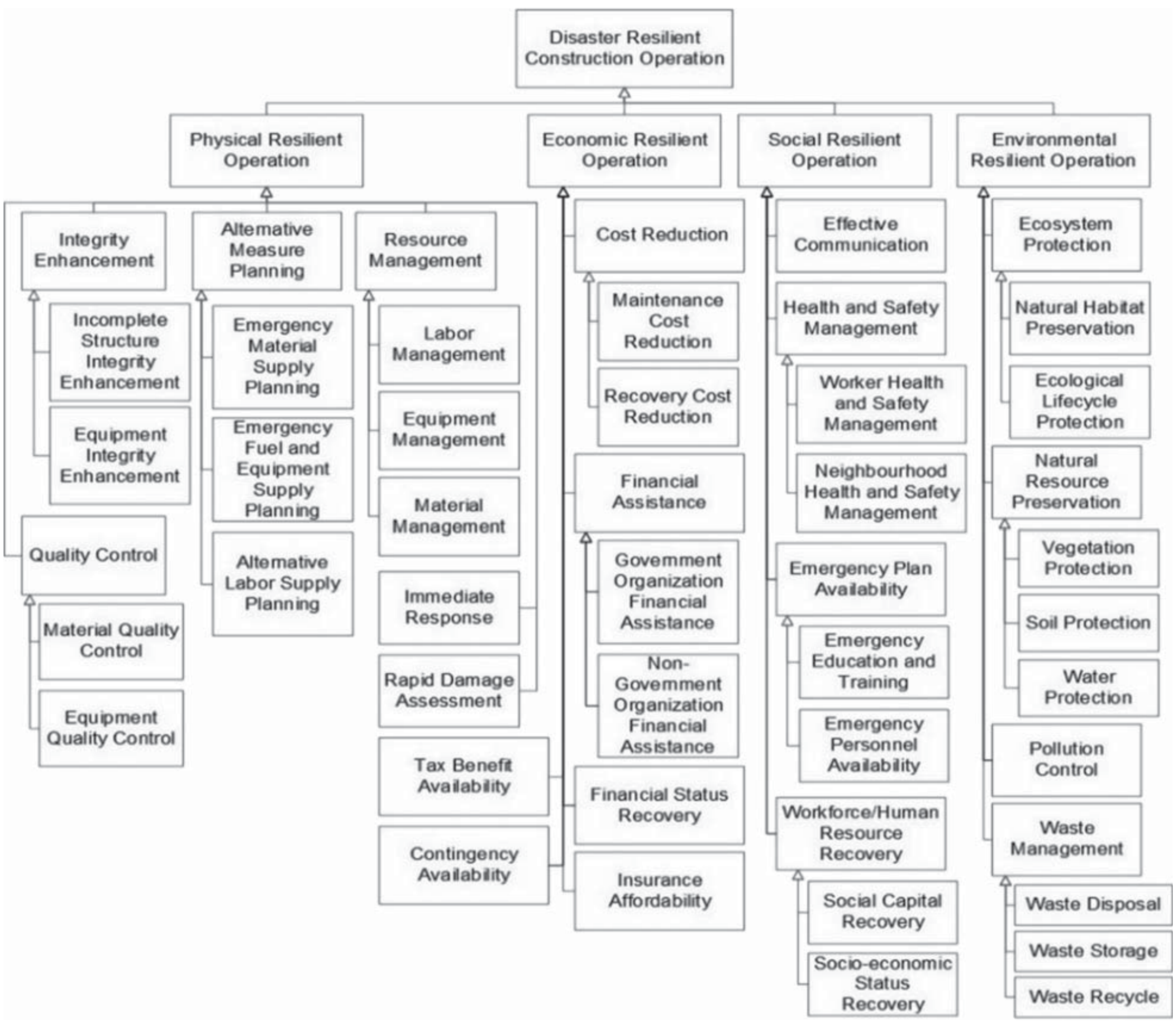

Fig. 95.2 Construction operation impact modality view

(4) Alternative measure planning is a process that provides a back-up plan for emergency supply of materials, equipment, labor, and services to ensure the functioning of the construction projects after the disasters.
(5) Immediate response is an action that is performed immediately after the disasters to save lives and mitigate property damage.
(6) Rapid damage assessment is an operation that is conducted immediately after the disasters to estimate or assess the resources needed to recover from the disasters.

For economic resilient operations, six sub-level concepts were defined:

(1) Cost reduction refers to the reduction in maintenance cost and recovery cost after the impact of the disasters.
(2) Financial assistance refers to the assistance provided by either the government or non-government organizations to recover the construction projects to its original functional level.
(3) Tax benefit availability refers to the provision of tax exemptions or benefits to support DRCOs.
(4) Insurance affordability refers to the affordability of insurance to support the recovery of property (e.g., incomplete structure, equipment) damage during the disasters.
(5) Contingency availability refers to the availability of reserved fund that could be utilized to recover in case of property damage due to the disasters.
(6) Financial status recovery refers to the recovery of financial situation of the construction projects after the disasters.

For social resilient operations, four sub-level concepts were defined:

(1) Health and safety management refers to the operation that supports the health and safety of workers and neighborhood around the construction sites during and after the disasters.
(2) Effective communication refers to the operation that facilitates effective communication between the individuals or organizations that are involved in the construction projects during the disasters.
(3) Emergency plan availability refers to the availability of an emergency plan that is used to mitigate the impact of disasters.
(4) Workforce or human resource recovery refers to the operation through which individuals or organizations attain their wellness or their full potential level after the disasters.

For environmental resilient operations, four sub-level concepts were defined:

(1) Ecosystem protection refers to the operation that is concerned with the preservation and restoration of surrounding ecosystems before the disasters.
(2) Natural resource preservation refers to the operation that is concerned with maintaining the water quality, soil, and vegetation during and after the disasters.
(3) Pollution control refers to the operation that is concerned with reducing the pollution in and around the construction sites after the disasters.
(4) Waste management is defined as the operation that deals with reduction, disposal, handling, and storage of the waste in and around the construction sites after the disasters.

95.4.2 Resilience Characteristic Modality View

The same concepts of DRCOs showed in the construction operation impact modality view is reclassified based on the characteristics of the disaster resilience: robustness, resourcefulness, redundancy, and rapidity. These four concepts are commonly used in describing disaster resilience in different domains (e.g., [2, 3, 6]). A robust operation refers to the operation that can withstand the disturbance and damage caused by the disasters, such as equipment integrity enhancement, ecological protection, etc. A resourceful operation refers to the operation that identifies the problems, mobilizes, and utilizes resources by setting up priorities during the disasters, such as natural resource preservation, financial assistance, etc. A redundant operation refers to the operation that provides alternative options or back-up plans for the construction projects to function in case of disasters, such as alternative measure planning (e.g., emergency material supply planning), contingency availability, etc. A rapid operation refers to the operation that optimizes the time for recovery to the original functioning level, such as immediate response, workforce/human resource recovery, etc.

95.4.3 Disaster Management Cycle Modality View

The concepts of DRCOs can also be classified based on the disaster management cycle: disaster mitigation, preparedness, response, and recovery [11]. A disaster mitigation operation is the action taken before the disasters to reduce and eliminate the impacts of the disasters, such as incomplete structure integrity enhancement, material quality control, insurance affordability, etc. A disaster preparedness operation refers to the preparations and plans made in advance to prepare for the disasters, such as emergency material supply planning, emergency personnel availability, etc. A disaster response operation refers to the immediate action during or after the disasters to save lives and to avoid further damage to the construction projects, such as immediate response, rapid damage assessment, etc. A disaster recovery operation refers to the action that helps to return to the pre-disaster states, such as pollution control, waste management, etc.

95.5 Evaluation of DRCOs-Onto

The proposed DRCOs-Onto was initially evaluated through answering competency questions (CQs). CQs are commonly used to evaluate semantic models [22]. In our proposed model, some examples of CQs are “who is involved in a DRCO?”, “what affects the implementation of a DRCO?”, “what are the sub-concepts of a DRCO?”, “is integrity enhancement a physical resilient operation?”, and “is recovery cost reduction an economic resilient operation?” The upper level concepts and relations of the DRCOs-Onto were manually checked for their ability to answer all CQs. The DRCOs-Onto successfully answered all CQs.

As part of our future work, we will further evaluate the representation, coverage, consistency, clarity, conciseness, extendibility, and applicability of the DRCOs-Onto by conducting expert interviews and application-oriented validation (through applying the DRCOs-Onto in a knowledge-based decision support system).

95.6 Application of DRCOs-Onto in a Knowledge-Based Decision Support System

Our proposed DRCOs-Onto will serve as a foundation for the development of a knowledge-based decision support system (DSS). This system can support the classification, access, and transfer of the knowledge of DRCOs, thus facilitating decision making on selecting and implementing the best disaster resilient operations on the construction sites. Our proposed knowledge-based DSS consists of four main modules: knowledge access module, knowledge classification module, knowledge summarization module, and knowledge recommendation module.

This paper focuses on discussing the knowledge recommendation module. This module aims to recommend different types of knowledge regarding DRCOs based on the users’ profiles, project contexts, and users’ interests. The system is structured based on the DRCOs-Onto. For example, the users’ profiles are linked to the “actor” in the DRCOs-Onto; the project contexts are linked to the “context”; and the users’ interests are linked to the “disaster resilient construction operation” with its different modality views. The system is able to retrieve the data on the users’ profiles, the contexts of the projects, and the users’ specific interests on DRCOs (e.g., disaster mitigation operation, social resilient operation, disaster recovery operation), and then delivers and recommends all relevant knowledge to the users. The system is connected to the publicly available online database, online journals, web pages that are created by individual researchers, organizations, professional societies, etc.

To illustrate how the DRCOs-Onto would serve as a foundation for the recommendation of knowledge on DRCOs, a use case scenario is provided (as shown in Fig. 95.3). In this scenario, a junior field engineer is involved in a project of a 5-story residential building in the City of Miami. The field engineer is not familiar with the regulations or specific natural conditions of the State of Florida, and he/she wants to know the robustness and disaster mitigation aspects of the DRCOs in Miami.

The knowledge-based DSS automatically extracts the data of the user’s profiles, project contexts, and users’ interests based on the DRCOs-Onto. For example, the data about the actor that is involved in the operation is extracted as “field

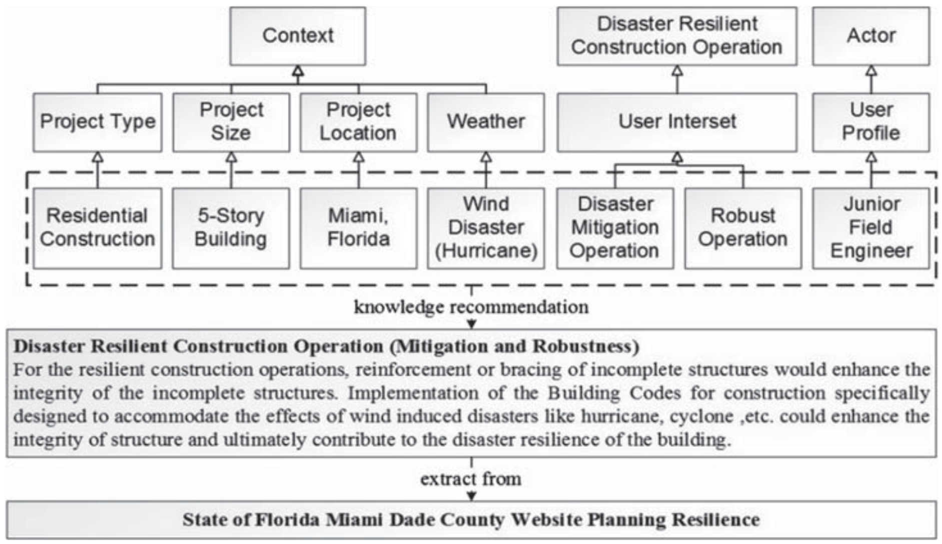

Fig. 95.3 Knowledge recommendation module in the proposed knowledge-based decision support system: an example use case scenario

engineer", and the data about the contexts are extracted as "5-story (project size)", "residential building construction (project type)", and located in "Miami" (project location). The system then filters and recommends the relevant knowledge on robust operations and disaster mitigation operations. The recommendations are customized based on the modality views in the DRCOs-Onto. In this case, the recommendation generated is constricted or filtered using the two interest areas: robustness and disaster mitigation. For example, one piece of knowledge related to reinforcing the incomplete structures is extracted from the Miami-Dade County website under "planning for resilience" section [14] and is recommended to the field engineer.

95.7 Conclusions and Future Work

This paper proposes an ontology-based semantic model that represents and reasons about the knowledge of disaster resilient construction operations (DRCOs-Onto). The proposed DRCOs-Onto is composed of concepts, inter-concept relations, and axioms. This paper focuses on discussing the higher-level model and the concept hierarchy of DRCOs. The proposed model aims to serve as the foundation for a knowledge-based DSS that allows for knowledge classification, access, and transfer on DRCOs, thus supporting the selection of the best DRCOs to implement. The model along with its potential application of knowledge-based DSS would allow construction professionals and stakeholders to receive, share, and transfer domain-specific knowledge on disaster resilience of construction operations.

In the future work, the authors will further develop and evaluate the proposed model. The model will also be implemented in the proposed knowledge-based DSS, and the performance of the different modules (i.e., recommendation, access, classification, summarization modules) will also be evaluated.

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