Ontology Construction for Human Non-Adaptive Evacuation Behavior in Building Fires

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Abstract. Many fire casualties result from evacuees' non-adaptive behavior. An effective human non-adaptive evacuation behavior ontology (HNEBO) can build a knowledge model that can contribute to a better understanding of non-adaptive behavior and the intervention for evacuees, yet, this has not been comprehensively investigated in the existing literature. In this study, the HNEBO is constructed based on 34 historical fire incidents following a three-step methodology. First, a five-tuple of HNEBO, consisting of concepts, relationships, functions, axioms, and examples, is constructed according to the Text2Onto and expert guidance. Then, the ontology is implemented using Protégé and is described with the web ontology language. Finally, the validity and integrity of the HNEBO are verified by qualitative evaluation and Ontology Improvement Tool quantitative evaluation. The findings of this study can provide emergency managers with the instrument for understanding human evacuation behavior and developing informed intervention strategies to guide occupants to evacuate safely.

1. Introduction

Building fires result in a significant number of casualties and extensive property damage. In 2021, there were 1,353,500 fires in United States (Nsc, 2023) in which 3,800 civilians lost their lives ; The same year in China, there were a total of 748,000 reported cases of fire, resulting in 1,987 deaths, and a direct economic loss of 6.75 billion yuan (Cfp, 2023). The irrational reactions and non-adaptive behavior of humans during a fire can create additional risks for evacuation (Cheng et al., 2019). Non-adaptive behaviors are actions that may obstruct or negatively impact the efficiency of the evacuation process (Wang et al., 2019). Typical non-adaptive behaviors include herding behavior, competitive behavior, return behavior, panic behavior, avoidance behavior, and so on. Scholars have conducted extensive research on various non-adaptive behaviors and their underlying conditions. In the era of big data, there is a wealth of fire reports and cases related to such behaviors. However, the knowledge and experience contained within these reports and cases have not been effectively extracted and utilized by emergency managers to manage non-adaptive behaviors during fire evacuations. Therefore, there is necessity to construct a knowledge model that facilitates better organization and management of this knowledge. In addition, in the process of non-adaptive behavior intervention, the use of diverse information collection and communication systems with varying domain vocabularies by different emergency management agencies can make information communication and interoperability challenging due to the heterogeneous semantics of the data (Liu et al., 2013). Establish a knowledge model can provide a unified interpretation for the concepts and relationships used in the application domain, enabling their sharing and computability. This facilitates information communication and interoperability.

While traditional methods of information management often store knowledge in the form of text or relational databases, they are not without their drawbacks when it comes to data storage, retrieval, and use. Ontologies, however, offer a solution to these issues by facilitating information organization, management, and understanding (Uschold and Gruninger, 1996). They have good potential to achieve content-based access, interoperability, communication, and other benefits (Ding and Foo, 2016). Ontology refers to the common understanding of certain fields of interest, which is usually considered as a set of classes (concepts), relations, functions, axioms, and instances (Gruber, 1993), and it is "a formal, explicit specification of a shared conceptualization" (Gruber, 1993). Based on such characteristics, the ontology can be used to analyze domain knowledge and to enable reuse of domain knowledge (Noy and Mcguinness, 2001). The use of ontology provides a shared framework of common understanding for a specific field enables communication between humans and application systems, and can have a significant impact on the processing of large amounts of distributed and computer-based heterogeneous information within the field. Often confused with ontology, the concept of a knowledge graph also represents knowledge through inter-group connections (Zhou et al., 2022), but primarily focuses on building applications that are defined by tasks. In contrast, ontology is defined from domain knowledge and includes definitions of concepts, relationships, and rules within a given domain. To achieve a structured understanding of domain knowledge for non-adaptive behavior, the ontology approach is preferred since it requires domain knowledge to be defined. To this end, this paper proposes a human non-adaptive evacuation behavior ontology (HNEBO) that can deconstruct non-adaptive behavior and its key influencing factors. This ontology can assist in the development of emergency management solutions and systems to manage non-adaptive behavior evacuation in building fires.

The ontological approach has found extensive applications in emergency management, particularly in the realm of building fires. Presently, there are two primary areas of application. Firstly, the ontology is utilized for representing safety knowledge relevant to fire. For example, Neto et al. (2021) built an ontology of evacuation behavior in building fire for developing a multi-agent intelligent system to evacuate occupant to a safe area. Tay et al. (2016) built a building information ontology to provide information support in case of fire emergency. Secondly, the ontology method is applied to the construction of fire emergency management knowledge. For example, the ontology was used to develop the emergency route recommended system for general emergency (Onorati et al., 2014) or fire emergency (Neto et al., 2022). Bitencourt et al. (2015) raised an emergency response protocol ontology for building fire. In order to realize semantic reasoning of intelligent emergency response application, Hristoskova et al. (2013) developed an emergency response ontology. Despite the significant impact of non-adaptive behavior, current research has not focused on the non-adaptive behavior ontology. Non-adaptive behavior is influenced by many factors, and the current knowledge systems for fire evacuation in historical cases and reports do not provide effective support for interventions targeting non-adaptive behavior.

This paper aims to address this gap, by developing the HNEBO to effectively organize and manage knowledge in the field of non-adaptive behavior. To construct the HNEBO, the ontology's scope and goals were first established. An automatic learning tool was then used to extract the ontology's concepts and relationships. Next, the functions, axioms, and examples of these concepts were determined. The ontology was then represented using the Protégé and the OWL knowledge representation language. To validate the effectiveness and completeness of the ontology, both qualitative and quantitative methods were employed. The construction of the HNEBO contributes to two areas: firstly, it enables the storage of knowledge related to fire non-adaptive behavior in a more scientifically manner, improving the efficiency of knowledge sharing and utilization in this field. Secondly, it provides a powerful reference for preventing and intervening in non-adaptive behavior during fire emergencies, enhancing the efficiency of fire emergency response and decision-making. The remainder of the paper is organized as follows: Section 2 introduces the methods utilized to develop ontology, Section 3 provides a detailed introduction to the HNEBO, Section 4 presents the ontology's validation, and Section 5 discusses and summarizes the findings.

2. Method

Several studies have already introduced commonly used methods and processes for ontology development (Mariano et al., 1997**,** Ding and Foo, 2016, Noy and Mcguinness, 2001, Uschold and Gruninger, 1996). Mariano et al. (1997) proposed four critical stages in developing an ontology, which have been used widely in ontology research (Neto et al., 2022, Neto et al., 2021). Drawing upon the above existing works, we have created HENBO based on the following four specific development stages.

2.1 Specification stage

In the first stage, the scope and objectives of the ontology were established. The key contents that needed to be clarified included the ontology's application area, the primary purpose for constructing it, its expected use, and the types of questions it should answer (Neto et al., 2021). As previously mentioned, the HENBO concerns human non-adaptive behavior during evacuation in building fire emergencies and its influencing factors. The objective of developing the ontology is to establish a knowledge representation model for non-adaptive behavior in building fires. The intended use of the ontology is to support the development of information systems capable of forecasting and intervening in non-adaptive behavior. Some of the questions that the ontology must answer included: 1) What factors contribute to non-adaptive behavior during evacuations? 2) How do these factors influence non-adaptive behavior? 3) How to intervene non-adaptive behavior considering these factors? The expected contributions of this ontology are twofold: 1) to enhance and consolidate knowledge in the field of non-adaptive behavior during building fires, and 2) to provide a knowledge model to support the development of interventions aimed at achieving efficient evacuation of humans during building fires.

2.2 Conceptualization stage

During the conceptual modeling stage, an ontology was described using a conceptual model based on previously defined specifications and requirements and a set of concepts or terms and their relationships were defined. Ontologies can be created from existing ontologies or from corpora, or through a combination of both (Uschold, 2000). Ontologies can be built with varying degrees of automation, from fully manual to semi-automated to fully automated approaches (Fernández-López, 1999). This study used a semi-automated approach to construct the ontology. Initially, 34 reported cases of fires were gathered as a corpus, and then the Text2Onto, an ontology learning tool, was utilized to extract concepts and relationships between them in the cases. In the literature, there exists a variety of ontology learning tools that have been proven capable of automating the extraction of ontologies (Park et al., 2010), including OntoLT, Text2Onto, OntoBuilder, and DODDLE-OWL. These tools borrowed methods from a range of fields, such as machine learning, natural language processing, and statistics, to extract concepts and their relationships from corpora. Text2Onto is one of the well-recognized ontology learning tools (Hajji et al., 2020, Babič et al., 2021), with its performance verified by several research studies (Ortiz, 2011, Hajji et al., 2020). Developed by the AIFB Research Institute at the University of Karlsruhe in Germany, Text2Onto can extract ontologies from unstructured text (Cimiano and Völker, 2005). It combines basic language processing techniques, such as tokenization, stemming, lemmatization, and shallow parsing, with machine learning methods. The language processing is based on the GATE2 framework (Cunningham et al., 2002), which begins with tokenization and sentence segmentation and then uses a part-of-speech (POS) tagger to generate appropriate syntactic categories for the tokens. Finally, the morphological analyzer and stemmer is used to do lemmatizing or stemming. Machine learning algorithms and natural language processing heuristics are utilized to identify and analyze concepts and their relationships, and the Text2Onto contains the following algorithms: Relative Term Frequency (RTF), Term Frequency Inverse Document Frequency (TFIDF), entropy, linguistic heuristics and so on. The difference of these algorithms is the criteria taken for calculation. The entropy algorithm was chosen in this study because it is a combination of C-value and NC-value, which is a common term degree calculation method in automatic term extraction research (Mittal and Mittal, 2013). The outputs of Text2Onto were further evaluated and corrected manually in this study.

2.3 Formalization and implementation stage

At this stage, the conceptual model was transformed into a formal model and the ontology was implemented by the knowledge representation language. As for implementation, there are many tools for building ontologies (Katifori et al., 2007), such as protégé, Apollo, OntoStudio and so on. Protégé is one of the most popular open-source platforms for constructing and describing ontologies. It has been widely used in research of building ontology, with numerous applications (Neto et al., 2021, Neto et al., 2022, Onorati et al., 2014, Uschold et al., 2015). Developed by the Center for Biomedical Informatics Research at Stanford University School of Medicine, Protégé allows users to construct ontologies directly on the conceptual model, without requiring knowledge of formal knowledge representation languages (Gennari et al., 2003). This study identified 1381 classes and 61 object properties and 37 data properties after conceptualization stage. Protégé was utilized to describe classes, subclasses, and object properties that represent relationships determined during the conceptual phase.

2.4 Maintenance stage

During the maintenance stage, the ontology that has already been implemented needs to be updated and corrected. The main tasks include strengthening domain knowledge acquisition by using relevant literature or interviewing domain experts, ontology evaluation, and implementing ontology documentation. Ontology evaluation is a crucial process that involves iterative judgment of its content relative to the reference, and it plays an important role in proving the effectiveness of ontology throughout the ontology development cycle. Evaluation methods can be classified into two categories: qualitative and quantitative evaluations. Qualitative methods involves domain experts evaluating the representativeness of the terms and relationships in the ontology to their professional domains, which can be achieved through interviews or questionnaires (Onorati et al., 2014). Previous studies have proposed many quantitative evaluation methods (Lourdusamy and John, 2018), such as OntoQA, Ontology Improvement Tool, Oops, RDF TripleChecker, and others. Among them, Ontology Improvement Tool (Gyrard, 2021) is a commonly used ontology evaluation platform that provides different tools that can calculate the pattern and instance measures of the ontology and evaluate its design and use, therefore, it was used in the evaluation of HNEBO.

3. HNEBO

Using Protégé, we created and described the classes, subclasses, the object properties and the data properties that characterized the relationships identified in the conceptualization stage. Fig. 1 shows a graphical representation of this characterization with the top class and its subclass. There are six subclasses behind the superclass, which are *Human* (any person who is involved in the fire evacuation process.), *Crowd* (the assembly of occupant in the fire scene), *Fire* (a rapid oxidation process, which is a gas phase chemical reaction resulting the evolution of light and heat in varying intensities), *Building* (a building or edifice, is an enclosed structure with a roof and walls standing more or less permanently in one place), *Emergency response* (a response effort by employees from outside the immediate release area or by other designated responders including, but not limited to, private sector emergency responders, mutual aid groups, local fire departments, or other qualified parties to an occurrence that results, or is likely to result, in an uncontrolled release of a hazardous material), and *Non-adaptive behavior* (the actions that may obstruct or negatively impact the efficiency of the evacuation process). In addition, the subclasses of *Human* are also shown in Fig. 1.

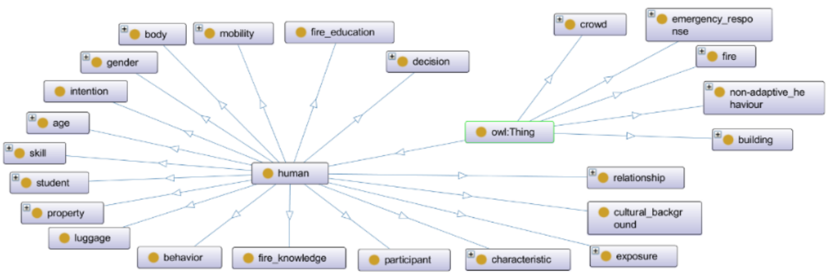

Fig. 1. Conceptual map of the human non-adaptive evacuation behavior ontology.

Object properties establish associations between instances of two different classes. Fig. 2 presents an example of the property guide that defines a relationship between an individual of the class *human* (domain) and an individual of the class *evacuation* (range) establishing that the human could have the function of guiding evacuation process.

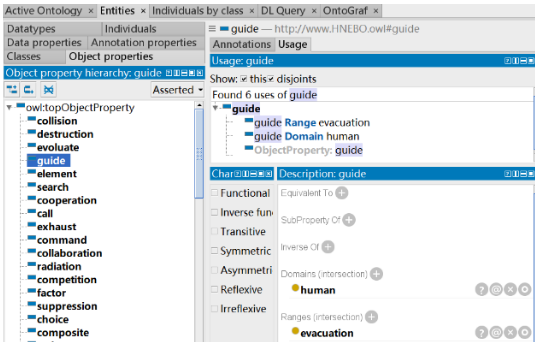

Fig. 2. The object property of *guide* in Protégé.

Data type properties link individuals of a class with primitive values. Fig. 3 shows an example of the property adult, which relates an individual of the class *age* to a primitive type Boolean.

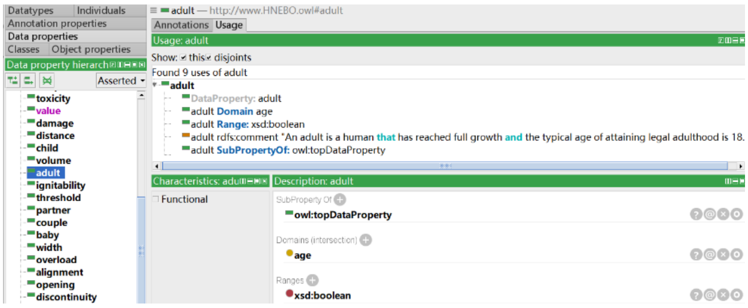

Fig. 3. The datatype properties of *adult* in Protégé.

4. Ontology Evaluation

The ontology development cycle (Asunción et al., 2006) includes the evaluation of the ontology in its entirety which consists of two main aspects. Firstly, the completeness of the overall structure was evaluated to determine whether the ontology meets the requirements of its definition scope and can answer the questions defined within it. Secondly, the structure and framework were validated, which involved checking the logical validity of the ontology. This section provides a comprehensive introduction to both types of evaluation.

4.1 Qualitative Evaluation

Qualitative evaluation is one of the important dimensions to assess the developed ontology, which can be used for assessing whether the concepts, attribute and the axiom can answer the questions and demands defined in the specification stage. These questions and demands are the origin of creating and developing ontology. In order to assess whether the developed ontology can answer the questions in the specification stage, we initially invited 11 emergency managers from large public buildings, who hold security management positions in subways or large shopping malls, to participate in semi-structured interviews. The interviews focused on the factors that need to be considered when intervening in non-adaptive behaviors during fire evacuation. There were four questions asked during the interview: 1. Does the plan provide intervention methods for non-adaptive behaviors? 2. How should panic and crowding situations be handled in practice? 3. Can the occurrence of situations such as crowd stampedes be predicted in advance? 4. To improve non-adaptive behaviors management, what aspects should be focused on in the future? After analyzing the interview results, 24 influencing factors were identified and summarized in Table 1. By comparing with the HNEBO, the results indicated that it was necessary to supplement properties and objects to the ontology constructed in this study. The supplemented properties and objects are highlighted in red in Table 1.

Next, we invited 10 experts in the field of evacuation behavior research to participate in a questionnaire survey assessing the factors and their importance in influencing non-adaptive behavior. Based on literatures review, we identified the key influencing factors, which are summarized in Table 2. Comparison with the ontology we constructed showed that the HNEBO effectively captured the influencing factors and mechanisms of non-adaptive behavior in the field.

Table 1. The factors influencing non-adaptive behavior summarized from interviews.

Occupant characteristics	Crowd characteristics	Fire characteristics	Building characteristics	Emergency response
• Mobility • Fire knowledge • Fire education • Emergency drill • Emergency training	• Crowd density • Crowd type	• Fire intensity • Temperature • Toxicity concentration • Smoke • Fire origin position • Time	• Building function • Building layout • Exit sign • Fire alarm system • Smoke detection • Building materials • The number of exits	• Capability • The number of incident commander • Emergency response plan • Economic cost

Table 2. The factors influencing non-adaptive behavior summarized from the literatures.

Occupant characteristics	Crowd characteristics	Fire characteristics	Building characteristics	Emergency response
• Age • Gender • Mobility • Exposure time • Student or not • Cultural background • Height • Luggage or not	• Assembly area • Crowd motives • Crowd type • Crowd density • Crowd density close to exits • Remaining occupant rate	• Temperature • Toxicity concentration • Smoke • Fire intensity • Fire origin position	• The number of exits • Doorway width • Exit location • Evacuation distance • Evacuation time • The fire resistance of building materials • Construction type • Exit visibility • Building layout • Building function • Exit sign • Emergency light • Fire extinguishing device • Fire alarm system	• Emergency response plan • Rescue response from governmental organizations • Incident commander

4.2 Quantitative Evaluation

To verify the correctness of ontology, relevant aspects of the ontology structure and system architecture must be considered, including syntax verification of classes, properties, and other ontology components, to ensure a comprehensive understanding of the knowledge model represented by the ontology. This paper utilized the Ontology Improvement Tool (Gyrard, 2021) to validate the ontology structure. The tool can be used in combination with other ontology tools, such as RDF Triple-Checker, Ontology Consistency, and OOPs (Ontology Pitfall Scanner) (Poveda-Villalón et al., 2014). It can be used to assess the integrity of the ontology structure, ensure correct publication of semantic web data, thereby identifying and addressing any potential issues. The interface of OOPS is shown in Fig. 4. By inputting the URI or the RDF of ontology, the results can be automatically outputted. Any critical problems must be solved because they can affect the ontology consistency, reasoning and applicability. The results showed that there were no critical problems to be solved for HNEBO.

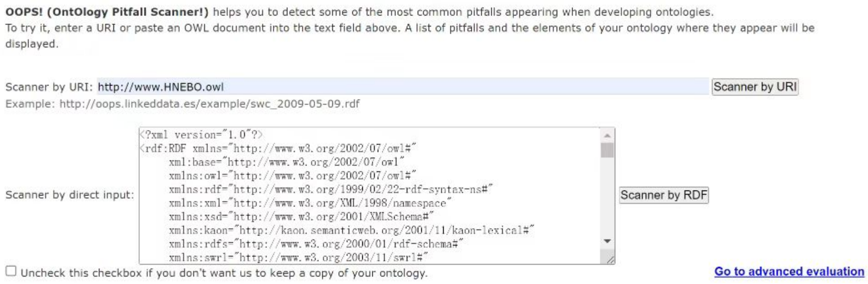

Fig. 4. The input interface of OOPs.

5. Conclusion

This paper presents the development of HNEBO, an ontology for representing non-adaptive behavior in fire evacuation, based on the analysis of reports of historical fire cases. The METHONTOLOGY method was utilized for constructing the ontology, which was implemented using the Protégé tool. The correctness and effectiveness of the ontology structure were validated using ontology validation tools. It is now publicly accessible at Ontology IRI: http://www.HNEBO.owl (Open by protégé). By providing a shared understanding and common language for communication between humans and heterogeneous systems, the constructed ontology has the potential to support knowledge representation in the field. Furthermore, it advances the understanding of non-adaptive behavior in fire evacuation and enables the development of more capable solutions and systems for non-adaptive behavior intervention.

This study makes two specific contributions. Firstly, the developed ontology enriches and expands the knowledge of constructing ontologies in the field of fire emergency management. While previous research has used ontology development in fire evacuation, earlier studies did not focus on non-adaptive behavior, overlooking its impact on fire evacuation efficiency. The developed ontology applies ontology development methods to the field of non-adaptive behavior in fire, promoting the integration and sharing of knowledge in this area. Secondly, the developed ontology defines the concept system of non-adaptive behavior in fire, which can aid the interventions in non-adaptive behavior during fire emergencies. There is a wealth of knowledge on non-adaptive behavior intervention in real fire cases and fire research, but this knowledge has not been applied effectively. The HNEBO ontology developed in this study is useful for storing and applying past knowledge and experience, enabling the development of solutions for non-adaptive behavior intervention.

It is important to note that creating an accurate and comprehensive ontology is not a one-time event, but rather an iterative process that lacks a completely correct method for establishing domain models. In addition, the ontology development process requires continuous iteration because developing a completely correct ontology is not possible. As such, HNEBO will be continuously refined based on new practical experience and theoretical knowledge in the future. In addition, future research can be carried out to develop effective management tools based on the ontology, which can ultimately be used to intervene in non-adaptive behaviors in fire practice.

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