THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :

Institut National Polytechnique de Toulouse (Toulouse INP)

Discipline ou spécialité :

Systèmes Informatiques

Présentée et soutenue par :

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le jeudi 12 mars 2020

Titre :

Ontology-driven services for interoperable multi-stakeholders operational disaster response

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Ecole doctorale :
Systèmes (EDSYS)

Unité de recherche :
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Acknowledgments

First of all, I wish to express my deepest gratitude to my supervisors, Mr. Bernard Archimède and Mr. Mohamed Hedi Karray. Thank you Bernard for your support and guidance during my thesis. Your wisdom and experience have inspired me a lot. Thank you Hedi for your availability and your continuous support. Your passion for work was, is, and will be my long-lasted motivation. You taught me how to surpass myself and to take things one step further. It has been a pleasure working with both of you.

I would like to thank Pr. Barry Smith and Dr. Neil Otte for their cooperation, careful reading, and constructive comments that helped me a lot.

I would like to thank Pr. Frederick Benaben for honoring my jury by presiding it. I am grateful to Pr. Christophe Merlo and Dr. Mounira Harzallah for accepting to review my manuscript. I also appreciate the participation of Mr. Antonio De Nicola.

I am also deeply thankful to all my colleagues and friends for their support during my thesis through very fruitful discussions and continuous moral support.

Last but not least, I would like to thank my family for their endless love and support.

Thank you all!

Linda Elmhadhbi

Abstract — Disaster response is a highly collaborative and critical process that requires the involvement of multiple emergency responders (ERs) ideally working together under a unified command to enable a rapid and effective operational response. It is a challenging task mainly because of the heterogeneity of the involved stakeholders and the critical nature of such event. Various ERs from different organizations must work together toward a successful resolution of the disaster. According to ERs reports and feedback, it is apparent that inadequate communication and a lack of information sharing among the ERs engaged on-site can adversely affect disaster response efforts. Within this context, we propose POLARISC, an interoperable inter-services software solution for reliable and timely information sharing for the operational management of large-scale disasters. The focus is on offering to all ERs a real-time operation picture of the situation in order to ensure effective collaboration and coordination among stakeholders. Accordingly, the first objective of this work is to capture the semantics of ERs knowledge. To do so, we propose an ontology that defines the knowledge of French emergency response doctrine, providing a shared vocabulary that covers a variety of interoperability concerns including data, services, processes, and business of each stakeholder. Because the diversity of ERs' vocabularies was bound, naturally, to complicate the design of the ontology, we adopted the principle of modularization. The idea is to develop separate ontological modules, one for each stakeholder. Furthermore, we used the upper-level ontology Basic Formal Ontology, as well as the suite of Common Core Ontologies, which serve as a suite of mid-level ontologies for our ontology modules. The use of upper-level ontologies facilitates the alignment among the different ontological modules and promotes data interoperability. Once the modular ontology POLARISCO is developed, we defined the mapping between the different modules. One strong point of the adopted ontological approach is that POLARISCO is tested by means of real data and validated by stakeholders and emergency experts. The second objective is to exploit the proposed ontology in order to guarantee a shared and semantically unambiguous information exchange across ERs. To do so, we propose an ontology-based messaging service, namely PROMES, performing the semantic translation of the information to be exchanged. Each stakeholder will receive the message according to his own vocabulary and with his own semantics. The semantic transformation of the message is based on the mapping that exists among stakeholders modules as defined in POLARISCO. PROMES is based on two algorithms; a textual transformation algorithm and then a semantic transformation algorithm. Using PROMES, it becomes possible for two ERs from different organizations to communicate meaningfully and with less ambiguity. To evaluate the proposed approach, POLARISCO is instantiated using real data of the 11/13 Paris terrorist attacks. The third and final objective is to propose a multi-criteria decision support service that supports ERs during victims' evacuation. The aim is to find the most appropriate healthcare institution according to the victims' states. The selection of the hospital depends, on the transport time, and on the availability of the needed resources including materials and staff. To do so, we propose, first, an ontological module that associates to each pathology the needed resources. Then, we propose an algorithm to check the availability of those resources, calculate the wait time to receive medical care in each hospital, and then select the most appropriate hospital.

Keywords: Ontology, semantic interoperability, multi-criteria decision support, disaster response.

Résumé — La gestion opérationnelle de situations de crise nécessite, selon l'importance et l'étendue de la crise, la mobilisation rapide et la coordination des différents services de secours. Malheureusement, cette coordination interservices est un exercice très délicat du fait de la diversité des acteurs intervenant sur le terrain et de l'hétérogénéité des différentes organisations. Aujourd'hui, il y a un manque de coordination, l'information n'est que très peu partagée entre les acteurs opérationnels et la communication n'est pas formalisée. Ces inconvénients conduisent au dysfonctionnement des réponses aux situations de crise. Afin de mieux répondre aux situations de crise, nous proposons POLARISC, une plateforme interopérable de coordination interservices pour la gestion opérationnelle de catastrophes visualisant en temps réel le théâtre des opérations. L'objectif de POLARISC est d'aider à la décision quel que soit le niveau de commandement. Pour atteindre ces objectifs, le premier enjeu de cette thèse est de garantir une interopérabilité sémantique entre les différents acteurs métiers pour assurer l'échange et le partage des informations. À cet égard, l'idée est de formaliser sémantiquement les connaissances des acteurs métiers de la gestion opérationnelle à l'aide des ontologies. En effet, nous proposons une approche fédérée qui représente les données, les services, les processus et les métiers de chaque acteur. Nous avons modélisé les connaissances des acteurs de secours en développant une ontologie modulaire (POLARISCO) comportant un module ontologique pour chaque acteur de secours et intégré ces derniers pour proposer un vocabulaire partagé. L'utilisation des ontologies de haut niveaux et des ontologies intermédiaires, respectivement « Basic Formel Ontology » et « Common Core Ontologies », facilitent l'intégration de ces modules et de leurs mappings. Le deuxième enjeu est d'exploiter ces ontologies afin de diminuer l'ambigüité et d'éviter la mal interprétation des informations échangées. Par conséquent, nous proposons un service de messagerie appelé PROMES transformant sémantiquement le message envoyé par un acteur émetteur selon le module ontologique de l'acteur destinataire. En effet, PROMES se base sur l'ontologie POLARISCO et sert à enrichir sémantiquement le message pour éviter tout type d'ambiguïté. Le fonctionnement de PROMES est basé principalement sur deux algorithmes ; un algorithme de transformation textuelle, et par la suite, un algorithme de transformation sémantique. Ainsi, nous avons instancié l'ontologie POLARISCO avec des données réelles de la réponse aux attaques terroristes de Paris en 2015 afin d'évaluer l'ontologie et le service de messagerie. Le troisième et dernier enjeu est de proposer un service d'aide à la décision multicritère qui permet de proposer des stratégies d'évacuation des victimes après le lancement du plan blanc. L'objectif est de trouver les structures hospitalières les plus adaptées à l'état de la victime. Le choix de l'hôpital le plus approprié dépend de la durée du transport, et surtout de la disponibilité des ressources matérielles et humaines, de façon à prendre en charge les victimes le plus rapide que possible. Notre étude comprend deux étapes : la première étape consiste à développer un module ontologique qui associe à chaque pathologie les ressources indispensables pour une meilleure prise en charge des victimes selon leurs états. La deuxième étape consiste à développer un algorithme qui permet de vérifier la disponibilité des ressources nécessaires, calculer le temps d'attente pour que la victime soit prise en charge dans chaque hôpital et par la suite choisir l'hôpital le plus approprié.

Mots clés : Ontologie, intéroperabilité sémantique, aide à la décision multicritère, gestion des catastrophes.

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List of acronyms

POLARISC ”Plateforme OpérationnelLe d’Actualisation du Renseignement Interservices pour la Sécurité Civile”

POLARISCO POLARISC Ontology

PROMES POLARISC Ontology-Based Operational Messaging Service

PROOVES POLARISC Ontology-Based Operational Victims Evacuation Service

PCC POLARISC Common Core

ERs Emergency Responders

EROs Emergency Responder Organizations

ORSEC ”Organisation de la Response de Sécurité Civile”

PMA Advanced Medical Post

PCO Operational Command Post

PRV Victims’ Gathering Point

DSM Director of the Medical Response

SINUS ”Système d’Information Numérique Standardisé”

FEI Framework for Enterprise Interoperability

CIMS Crisis Information Management Systems

EDXL Emergency Data Exchange Language

BFO Basic Formal Ontology

CCO Common Core Ontologies

RO Relations Ontology

DO Disease Ontology

ERO Eagle-i Resource Ontology

SPARQL Simple Protocol and RDF Query Language

OWL Web Ontology Language

CQs Competency Questions

GT	Glossary of Terms
GUI	Guided User Interface
MCDM	Multi-Criteria Decision Making
AHP	Analytical Hierarchy Process

Introduction

Context and motivations

Throughout history, disasters, whether man-made or natural, have caused the loss of human life and property damage that can directly or indirectly affect negatively an entire nation. The need to face their suddenness, complexity, and chaotic nature makes disaster management challenging [1]. The focus of disaster management is to reduce the risk posed by these disasters and to limit their impacts. By definition, disaster management is a multifaceted process that consists of planning for reducing the impact of disasters, responding immediately, and then taking the appropriate steps to recover after a disaster has occurred. Disaster response requires collaboration from multiple agencies to stop the threats and assure prompt and appropriate assistance to victims. Specifically, when a disaster occurs, a streamlined response organization at the strategic, tactical, and operational levels is crucial to handle the disaster effectively. An appropriate operational response depends on a detailed plan with clearly articulated roles and responsibilities. It involves diverse Emergency Responders (ERs) from different Emergency Response Organizations (ERO) ideally working together under a unified command.

The first key factor for the success of large-scale disaster response is the collaboration among the involved stakeholders. However, such collaboration is often not achieved. Almost without exception, after-action reports from major disasters have expressed concerns over the EROs' ability to collaborate and cited communication difficulties as a major failing and challenge [2]. An example can be found in the concluding report on the terror attack in Norway on June 22, 2011, which states that the various EROs were unable to communicate effectively and coordinate their efforts. These challenges were highlighted also by the 9/11 and 11/13 Paris terrorist attacks [3] [4]. Even though almost fourteen years passed between these two terror attacks, the same response deficits appear in both. In the 11/13 Paris attacks, for instance, there were two sites where victims did not receive medical care due to a lack of communication between firefighters and healthcare units [4]. In addition, police forces claimed that [5]:

- "by the time the information gets out and finds its way up to the central organization, mobilizing the specialized units takes a relatively long time."
- "our police are not organized along local lines. Everything has to filter up to the central organization at the prefecture."
- "We have a police force that is disconnected from the field."

Effective collaboration cannot take place without the support of good communication. However, the process of communication among ERs has two barriers. First, ERs use radio communication channels with a different frequency for each ERO which makes inter-organizational communication extremely difficult [6]. In the Paris attacks, firefighters and healthcare units pointed out that the use of radio communication was unsatisfactory during the different interventions [7]. Second, because they reflect different areas of expertise, EROs use differing terminologies, which are difficult to reconcile. ERs use different terms for the same things or several interpretations of one expression [8]. The resultant semantic heterogeneity of information and the absence of a common language leads to ambiguities, misunderstandings, and inefficient information exchange among those involved, which can impede the response process and slow decision making.

The second key factor for the success of large-scale disaster response is the availability of useful and real-time information to facilitate the decision-making process. In fact, ERs need accurate and relevant information in a timely manner for appropriate resource deployment and dispatching and to successfully ensure key processes of disaster response including mainly mass evacuation. ERs work together to ensure victims' gathering, triage, and evacuation to the appropriate healthcare institutions to receive the needed medical care. In the light of the disaster complexity, the rapidly evolving events, the enormous amount of generated information, and the huge volume of casualties, ERs may be overwhelmed and subsequently, poor decisions may be made. As a result, staff and equipment are sub-optimally used, and victims are negatively impacted. In fact, the possibility of transporting the victims to one of several hospitals and the dynamic changes of the healthcare resources' availability make the decision process more complex. Often the nearest hospitals are rapidly overloaded and can no longer receive new victims. The response to the 11/13 Paris attacks underlined the need to improve victims' evacuations strategies in order to preserve victims' life [9].

With regard to all the aforementioned features, the efficiency of disaster response is challenged by the ability of ERs to communicate and share semantically accurate information towards coordinating their processes and to make the best decisions regarding the allocation of the available resources in order to save the maximum of lives.

Despite the existing variety of research avenues proposed in the literature dealing with different aspects of disaster management, we notice the need for a new solution that considers the different identified challenges of the operational disaster response. Solving these challenges are the main cornerstone to build such a solution.

Thesis objectives

The aim of this thesis is to focus on the challenges of the operational disaster response in order to improve the response process and reduce causalities. Specifically, the main objectives of this thesis are summarized as the following:

- Empower information exchange and ensure mutual understanding among stakeholders with respect to the terminology used by each ERO to build a coherent response to the disaster.

- Support better decision making towards facilitating and improving the process of victims' evacuation.

Research questions

To achieve the aforementioned objectives, the following research questions should be considered:

- How to formalize the specificities of each ERO's terminology?
- How to address the semantic heterogeneity issue that impedes information exchange among ERs?
- How to exploit information and to empower decision-making in order to determine the most appropriate hospitals for victims' evacuation?

Contributions

To address the identified challenges of the operational disaster response process, and to reach the cited objectives, we follow in this work an ontology-driven approach. Ontology is considered as a formal and explicit specification of a conceptualization that facilitated knowledge capturing, representing, structuring, sharing, and reuse [10]. It has been used in various domains to enable semantic inference and reasoning for more intelligent systems as well as to promote semantic interoperability among heterogeneous information systems.

The contributions of this thesis are threefold. First, we propose an ontology that formalizes the complex knowledge of the different stakeholders in order to provide a common semantic framework for the French ERs including firefighters, healthcare units, police forces, gendarmerie, and public authorities. Because the diversity of ERs' vocabularies was bound, naturally, to complicate the design of the ontology, we adopted the principles of modularization to build our ontology. Moreover, to develop a consistent and useful ontology, we followed a set of best practices [11]. These latter include the use of a domain-neutral upper-level ontology and the reuse of existing ontologies. The use of upper-level ontology is fundamental to promote semantic interoperability among the different proposed ontological modules by enabling their integration.

Second, we explore the ontology to determine the meaning of the information to be exchanged in order to establish semantic interoperability and to empower data exchange across ERs. Accordingly, we propose an ontology-based messaging service that resolves terminology inconsistencies and ensures semantically unambiguous information exchange among stakeholders. ERs will continue to use the terminologies to which they are accustomed, but the system will ensure a mutual understanding by enabling a semantic translation of the information to be exchanged.

Third, the ontology is exploited by means of a multi-criteria decision support service in order to assist ERs and improve the process of victims‘ evacuation. Specifically, the ontology is queried to find out the required healthcare resources including staffing and equipment for the victims’ needs. Then, the victim-to-hospital assignment process depends on the exploitation of the availability of the needed resources, the victims’ wait time to receive the medical care, and the hospital proximity to the disaster site. Figure 1 encapsulates the mind map of the research methodology.

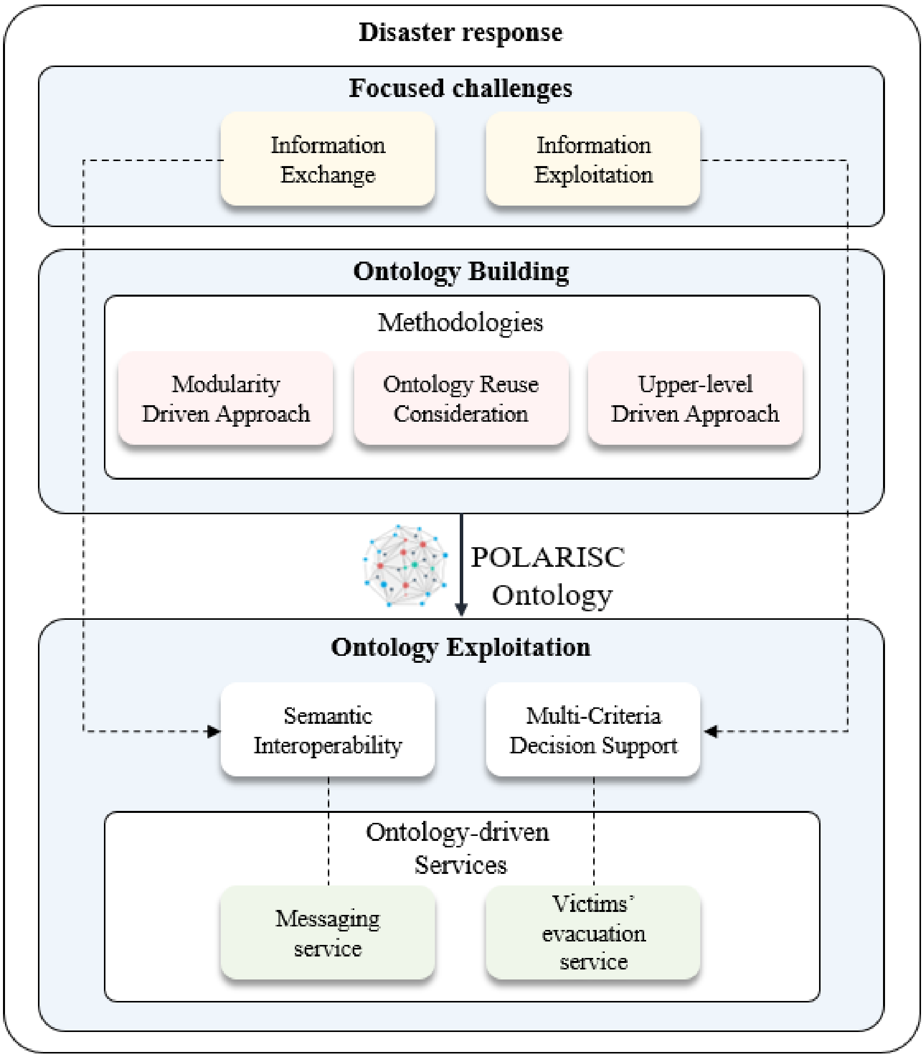

Figure 1: Mind map of our research methodology.

Thesis outline

In the following, a brief synopsis of the thesis structure is presented. Chapter one is divided into two parts. The first part presents the backgrounds and the state of the art. We first provide an overview of the main phases of disaster management and the different levels of disaster response. The disaster response process is studied to illustrate the role of each ERO and the value of communication and coordination among them. Then, the keystone challenges that should be considered for an efficient operational disaster response are identified. Second, we define interoperability and overview some relevant disaster management systems proposed in the literature, focusing specifically on how they deal with interoperability and how they respond to the operational challenges. Third, we present a research overview of existing ontologies proposed in the operational disaster response context. Note that there is a complementary state of the art at the beginning of each chapter specific for the respective contribution. In the second part, and based on the identified research gaps from the state of the art, we introduce the orientations and the scope of our work.

Chapter two gives an overview of the proposed ontology that semantically captures the knowledge of the different ERs following the different steps of the adopted ontology building methodology. Specifically, we present how ERs' knowledge is acquired, conceptualize, and formalized. Then, we demonstrate how the implemented ontology is evaluated and validated using a real case study.

Chapter three presents the proposed solution to promote semantic interoperability and to improve information exchange across ERs. Accordingly, the proposed ontology is exploited by a messaging service that enables semantic translation of the information to be exchanged. The architecture and the mechanism of the proposed service are explained in detail. Precisely, we describe the ontology mapping and the semantic translation approach. Afterword, we demonstrate how an act of communication can be performed between stakeholders from different ERO and we discuss the evaluation and the validation of the proposed service.

Chapter four depicts the proposed multi-criteria decision support service that aims to find the most appropriate hospital to transfer the victims in terms of the availability of the needed healthcare resources and the rapidity of receiving the suitable medical care. The proposed approach provides the ranking of the different hospitals from the most appropriate to the less appropriate. The architecture of the system and a detailed description of the multi-criteria decision support process are presented. The evaluation and validation of the service are then discussed.

Finally, in the conclusions, we summarize the obtained results and then we provide the potential future directions for our work.

Chapter 1

Background, State-of-the-Art, and Orientations

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1.1 Introduction

In this chapter, we will introduce some basic backgrounds and an understanding of the positioning and orientations of the study from a scientific point of view. Specifically, we will start by defining disaster, disaster management, and disaster response process levels and challenges. Next, we study, on the one hand, existing crisis information management systems in terms of interoperability and usability in the operational response to large-scale disasters, on the other hand, exiting disaster response ontologies and meta-models. At the end of the state of art, the research orientations are presented.

1.2 Background and state of the art

1.2.1 Disaster management

1.2.1.1 What is a disaster and what is disaster management?

Despite the fact that there is a difference between the terms emergency, crisis, and disaster, in the literature, they are being used interchangeably and sometimes in combination. However, they could mean three very different but interconnected things [12]. Understanding their meaning may enable better management and limit their impacts. Various literature reviews have been conducted in order to improve the understanding of these three phenomena. There is no unique definition and understanding of what are they and what they encompass.

According to the US Department of Homeland Security National Response Framework, a disaster is defined as any natural or man-made incident, including terrorism, that results in extraordinary levels of mass casualties, damage, or disruption severely affecting the population, infrastructure, environment, economy, national morale, and/or government functions [13]. A crisis is defined as a situation in which substantial decisions have to be made in a minimum of time, while as a disaster, it should maintain management procedures under conditions of major technical emergency [14] [15]. An emergency is defined as “an imminent or actual event that threatens people, property or the environment and which requires a coordinated and rapid response” [16]. In [12], the authors concluded that the term emergency does not share many common features comparing to the other two terms. As regards to crisis and disaster, they have a lot of common features, so that they can be used interchangeably. The sudden nature of these events and the potential threats of injury, loss of life, and properties' damage are the common features of the three terms. To summarize, both emergency and crisis would lead to a disaster if the event were mismanaged or neglected. In this thesis, we use the term disaster as it fits our motivations as introduced in the previous chapter.

Small and large-scale disasters can occur at any time, and the consequences can be serious and enormous. The need to face the suddenness, complexity and the chaotic nature of disasters, make disaster management becomes more challenging [1].

1.2.1.2 Disaster management process

Disaster management is “the process of planning and taking actions to minimize the social and physical impact of disasters and reduce the community's vulnerability to the consequences of disasters” [17]. It deals with the coordinated efforts of various emergency responders organization (EROs) to organize and manage resources and roles towards offering support to the affected people and limiting the impacts of the disaster.

Disaster management is a multifaceted process that comprises the following four main phases (see Figure 1.1): PPRR (Prevention, Preparation, Response, and Recovery). Each of these phases may be identified by the approach they take to lessen the impact of the disaster [18]:

1. **Prevention** involves taking the appropriate strategies to prevent a potential hazard or a natural phenomenon from causing harm to either people or the environment. It is based on hazard identification and vulnerability assessment.
2. **Preparation** is a state of readiness and is brought about by taking suitable measures to respond in advance of a disaster. Preparation measures include the maintenance of resources, the training of the personnel and the formulation of disaster response plans.

3. **Response** is an aggregate of processes that seek to counter disasters' harmful effects as rapidly and effectively as possible by mobilizing the appropriate organizations and resources in a coordinated manner. Examples include search and rescue, firefighting, mass evacuation, and restoring public order. Response measures are directed towards saving lives, protecting properties, and dealing with immediate damage caused by the disaster.

4. **Recovery** refers to the process of returning the affected area back to normalcy. The recovery process includes restoration and reconstruction in order to reinstate the proper level of functioning following a disaster.

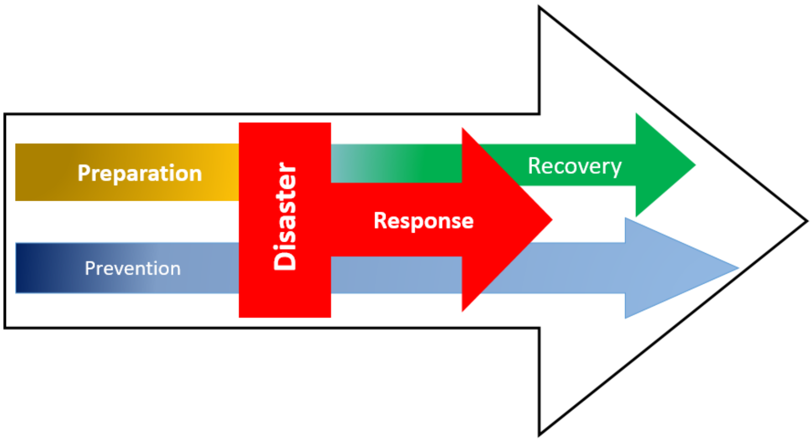

Figure 1.1: The disaster management process (International Federation of Red Cross and Red Crescent Societies).

1.2.1.3 Disaster response levels

The focus of this thesis is on the response phase of disaster management. When a disaster occurs, a streamlined response resulting from well-coordinated organizations is crucial to its effective handling. This involves knowing what sequence of actions is needed in order to generate a maximally effective response. Disaster response includes decision making, stakeholders assignment, and resource allocation in order to re-establish normality. Planning processes that occur as part of a disaster response may be conceived as occurring at different levels that correspond to the traditional "levels of war" as shown in Figure1.2; the strategic level, the tactical level, and the operational level [19].

The strategic level

Strategic management is the highest level of decision making handled by public authorities. These latter assume that the command of the disaster response process is determined on the basis of the type and magnitude of the disaster and of the administrative division of the country in which the disaster occurs. The role of the strategic level consists of defining

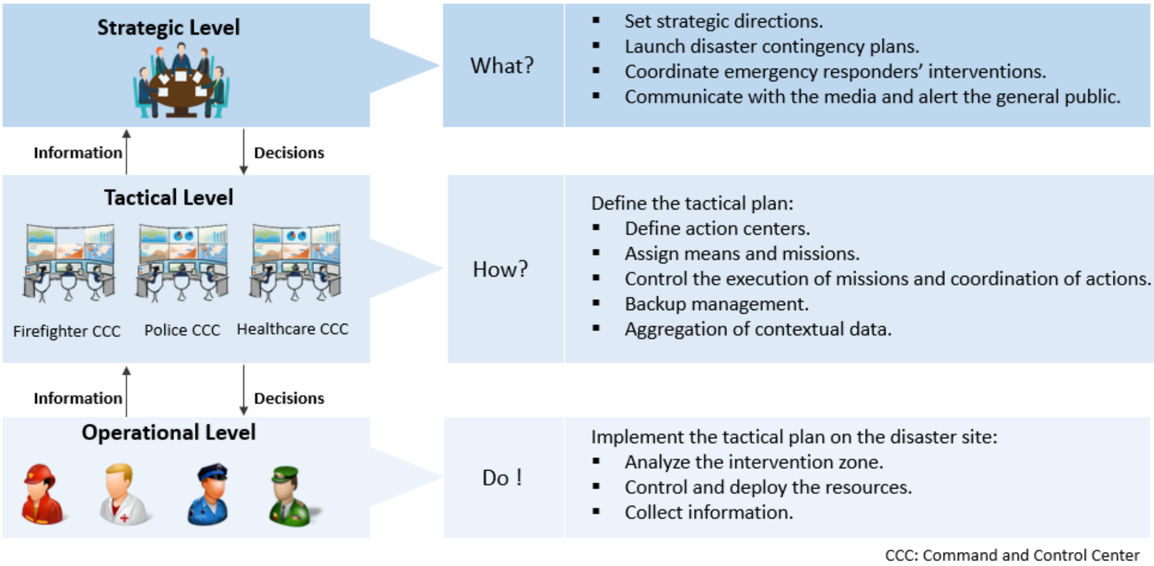

Figure 1.2: Disaster response levels.

strategies and directing the appropriate organizations to engage in the disaster response [20]. It involves, on the one hand, determining high-level directions, including resource priority decisions, assignment of roles and responsibilities, and overall courses of action. On the other hand, public authorities play a key role in disaster communication; in addition to inter-agency communication, they communicate with the media to provide valuable information about events in order to alert citizens.

France, for example, is a unitary state in which strategic command depends on four organizational levels as shown in Figure 1.3. At the national level, the interior minister of France is responsible for civil protection across the whole country. He takes control of the inter-ministerial operational crisis management center. This latter ensures round-the-clock monitoring of large-scale rescue operations and coordination of resource allocation. At the next level down, zone prefects are in charge of zone operations centers, which ensure the coordination of the rescue operations within their jurisdiction. At the department level, the prefect is in charge of the departmental operations center. The prefect, as the representative of the government of France in each department (division), relies on the operational command post (PCO), which is located in a safe place near the disaster area, to coordinate the various stakeholders on the disaster field. At the communal level, each commune has its own mayor responsible for everyday public safety and security on the territory of the municipality. In case of disaster, the mayor is the first to step in. He or she manages resources and coordinates communication among all actors who may be implicated in the disaster response process [21].

The organization of the civil security response plan, known by its French initials ORSEC plan ("Organisation de la Response de Sécurité Civile"), provides the general framework of the response process. It defines the chain of command, the responsibility of each actor, and the communication protocols. Moreover, it defines the organization and the functioning of the

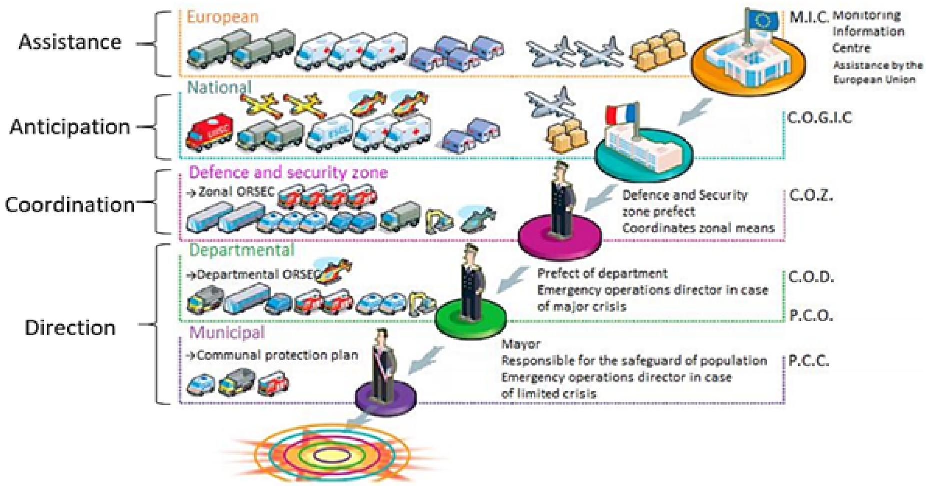

Figure 1.3: Structure of the French plan for disaster response [**min**] (Ministry of the Interior, 2009).

crisis cell which is a joint structure bringing together representatives of the different involved stakeholders. The crisis cell ensures a permanent liaison with the public authority, command and control centers, and actors working on the disaster site. Response efforts need to be coordinated through the oversight of a crisis cell and adapted as the disaster develops.

Once a disaster occurs, the ORSEC plan is launched. Calling the plan into action means activating five operational cells: fire brigade, healthcare units, police and public order, transportation, and transmission [22]. In practical terms, ORSEC concerns: the establishment of a civil defense network, the definition of the operational doctrine, the implementation through exercises, and the continuous improvement through feedback and lessons learned [23].

The tactical level

Concerning the tactical level, it means translating strategic objectives into actions. It involves defining the necessary steps for implementing a strategy in order to address a potential threat. The tactical level is composed of stakeholders' commanders, knowing that there is a separate command and control structure for each ERO. Their role is to outline what stakeholders must do on the disaster site to successfully respond to the disaster and end threats. It includes also the allocation of resources of each unit on the disaster site according to their availability, task priority, and geographic proximity.

The operational level

The operational level consists of the major operations conducted in order to accomplish the required tactical plan on the areas of operation (see Figure 1.4). Such operations are intensely monitored since the involved ERs are confronted with uncertainty, time pressure, and highly dynamic situations. It is also a highly collaborative process that requires the involvement of different government agencies and multiple emergency responders (ERs) such as firefighters, police forces, healthcare units, and so on. Ideally, these various ERs should work together under a unified command to reach the shared goal of rapid and effective operational response. The operational level defines individual tasks to be performed using the available resources. When responding to a disaster, the involved ERs have different roles and responsibilities. For example, firefighters and healthcare services handle the victims' rescue and saving lives, police forces and gendarmerie ensure the public order. Usually, the ERs are dispersed at different geographic locations; some work at the PCO, and some work on the disaster area. The collaboration among these ERs necessitates quick and efficient information sharing.

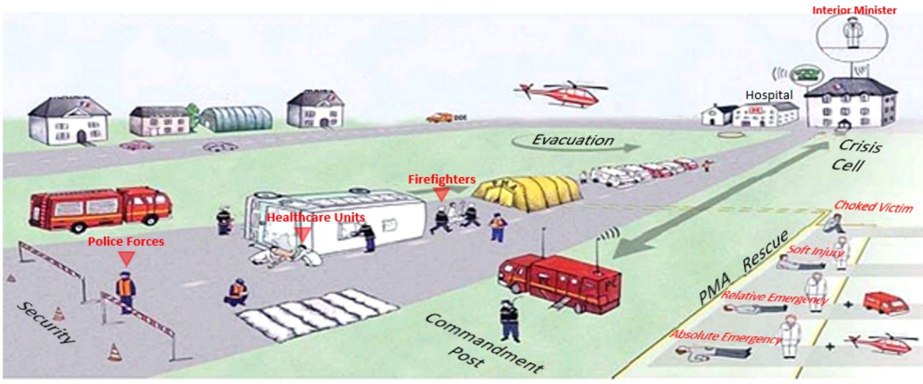

Figure 1.4: Mobilization of the operational stakeholders on the disaster site (firefighters, healthcare units, and police forces) ("Plan ORSEC Nombreuses Victimes", 2012).

1.2.1.4 Study of the disaster response process

In order to comprehend how the involved EROs, operate and coordinate their activities when responding to a disaster and towards enhancing the understanding of the role of each actor, here follows an explanation of the disaster response process as a workflow. In fact, the term workflow, or also called business process, is "a set of one or more linked procedures or activities which collectively realize a business objective." (Workflow Management Coalition, 1999). It determines the order of execution of activities.

Let's start with the strategic level. Once the disaster is detected, the interior minister launches the ORSEC plan by mobilizing the needed ERs, activates the crisis cell and the PCO, and alerts the citizens by informing the media. Then, he ensures the supervision of the response evolution.

The crisis cell is in charge of collecting the relevant information from the tactical level to identify with precision the disaster area to order the definition of three zones. The exclusion zone is an area where only the police units are allowed to go for reasons of safety. The controlled zone is where the medical team of the police unit transfers the victims to the support zone where we found the healthcare teams and the firefighters. Once the different zones are defined, the crisis cell sets up the strategies of facing the threats and evacuating the victims. Moreover, the crisis cell is responsible for the coordination between actors on the disaster site. Once the threats are over, the crisis cell asks for the activities reports from the

ERs so as to analyze them and send them to the interior minister to publish the official final report.

Concerning the tactical level, each commander is in charge of mobilizing his teams and allocating the appropriate resources on the disaster area. Then, he leads the teams' actions on the disaster site and in case of lack of means or staff, he is responsible for sending backups. In addition, he ensures the sharing of information with the strategic level by informing the crisis cell about what is happening on the disaster site. That is, the tactical commanders play the role of the gate between the strategic and the operational level.

Specifically, the police commander orders his teams to define the security perimeter and the different zones of exclusion, control, and support, and he leads their actions to face the threats and to secure the zones. The gendarmerie commander is in charge of conducting the actors' actions on the disaster site in order to isolate and secure the perimeter of security. The firefighters' commander orders fire extinction, victims' extrication, and rescue. The healthcare commander orders the installation of the advanced medical post (PMA), which is the centralized point for casualties rescue on the disaster scene, and victims triage. He is responsible for managing the massive afflux of victims by checking the availability of resources in the hospitals and orienting the evacuation of victims. The commanders of the different ERs coordinate their activities so as to save the victims from the potential risks.

Concerning the operational level, firefighters, healthcare units, police forces, and gendarmerie respond to these extremely volatile and difficult circumstances. Once they arrive on the scene, the first task to perform is the recognition of the zone. The elite unit of the police forces focuses on finding, apprehending or neutralizing the threats. Another team of police forces takes charge of the setting up of the security perimeter by dividing the zones (see Figure 1.5). Then, they start the extraction of victims to the controlled zone in order to evacuate the affected area and transport people at risk to safety. Depending on the victims' state, either they will be transferred to the support zone or they receive the first aids from the medical support team of the police forces and then they will be transferred. Once, the threat is over, the exclusion zone could be removed.

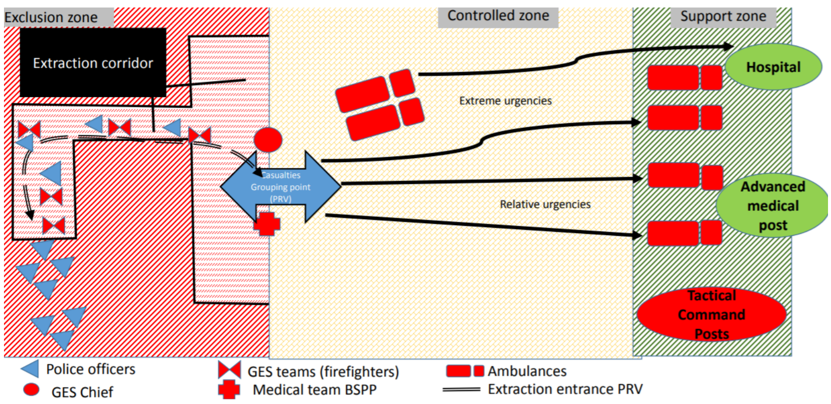

Figure 1.5: ERs' actions on the disaster site [7].

The gendarmerie teams are responsible for securing and isolating the zones defined by the police by prohibiting the access of the public or the media in order to facilitate the arrival of the needed means.

Once the victims are transferred to the support zone, here comes the role of healthcare services. First, they start by installing the PMA and fixing the point of victims' gathering (PRV). Second, they sort the victims in the PRV. If the victim has a relative emergency, he will receive an instant medical care in the PMA. If he has an absolute emergency, he will be transferred immediately to the hospital. Finally, if the victim is unscathed but choked, this will require the activation of the medico-psychological emergency cell.

Concerning the firefighters, they are divided into three teams. The first team collaborates with the healthcare units in the gathering, rescue, and evacuation of victims. The second team is responsible for searching and extrication of potential victims. The third one takes in charge of the extinction of possible fires.

In case of insufficient means or staff during the execution, the commander of the operational team demands backup from the tactical commander. Figures 1.6, 1.7, and 1.8 show the workflow of stakeholders processes and highlight the interactions that occur among the different levels of disaster response (strategic, tactical, and operational level).

One may conclude that, despite their differences, the strategic, tactical, and operational levels of disaster response are integrally related. Achieving efficient information exchange between these levels is essential for a successful disaster response. In fact, because of the hierarchical command and control structure of ERs, information flows vertically throughout the levels [24]. Specifically, information issue from the strategic level to the tactical level at first and then to the operational level, and vice versa. For instance, once the police forces secure the intervention zone, the healthcare units could intervene and evacuate the victims. To do so, the steps of information flow is like follow (see Figure 1.9); the operational commander of the police forces informs the respective tactical commander (1) who reports it to the crisis cell (2). The crisis cell informs the public authority (3) who orders the intervention of the healthcare units (4). The crisis cell informs the healthcare commander about the decision (5). This latter defines the evacuation plan and requires its execution on the disaster site (6).

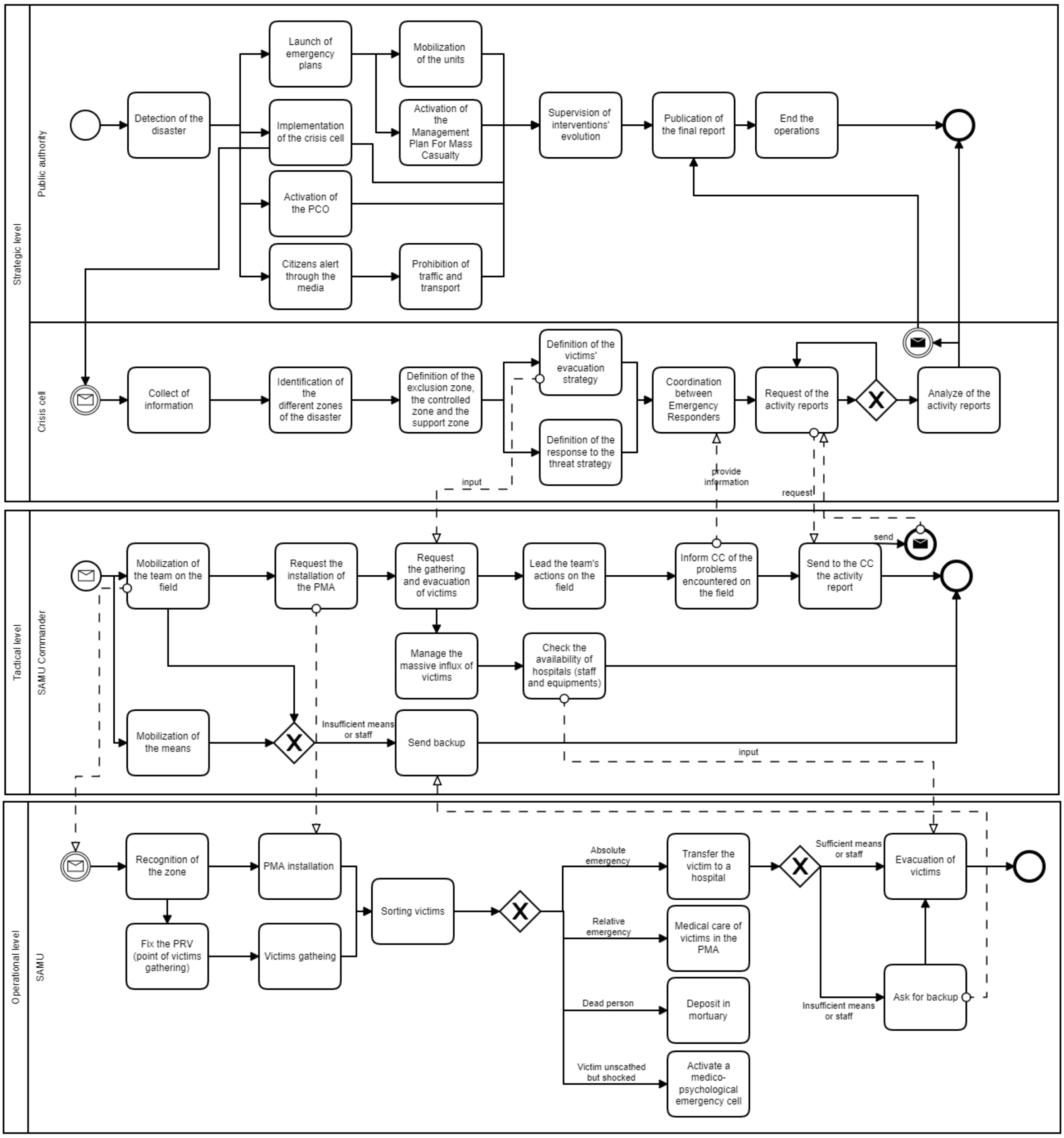

Figure 1.6: The workflow of healthcare units' process (strategic, tactical, and operational levels).

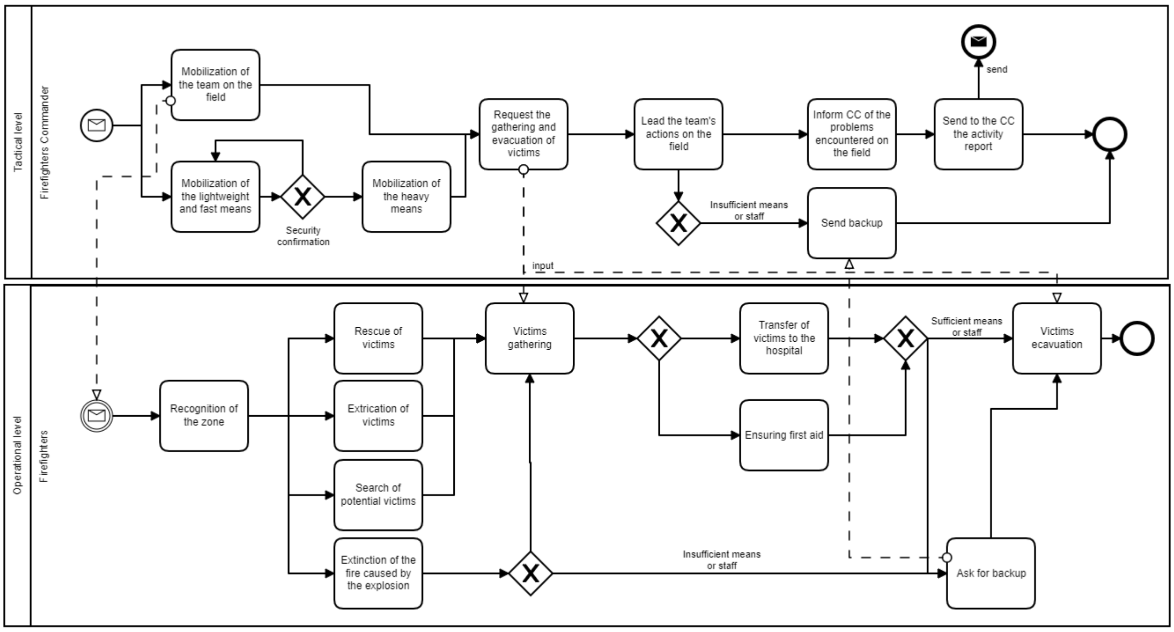

Figure 1.7: The workflow of firefighters' process (tactical and operational levels).

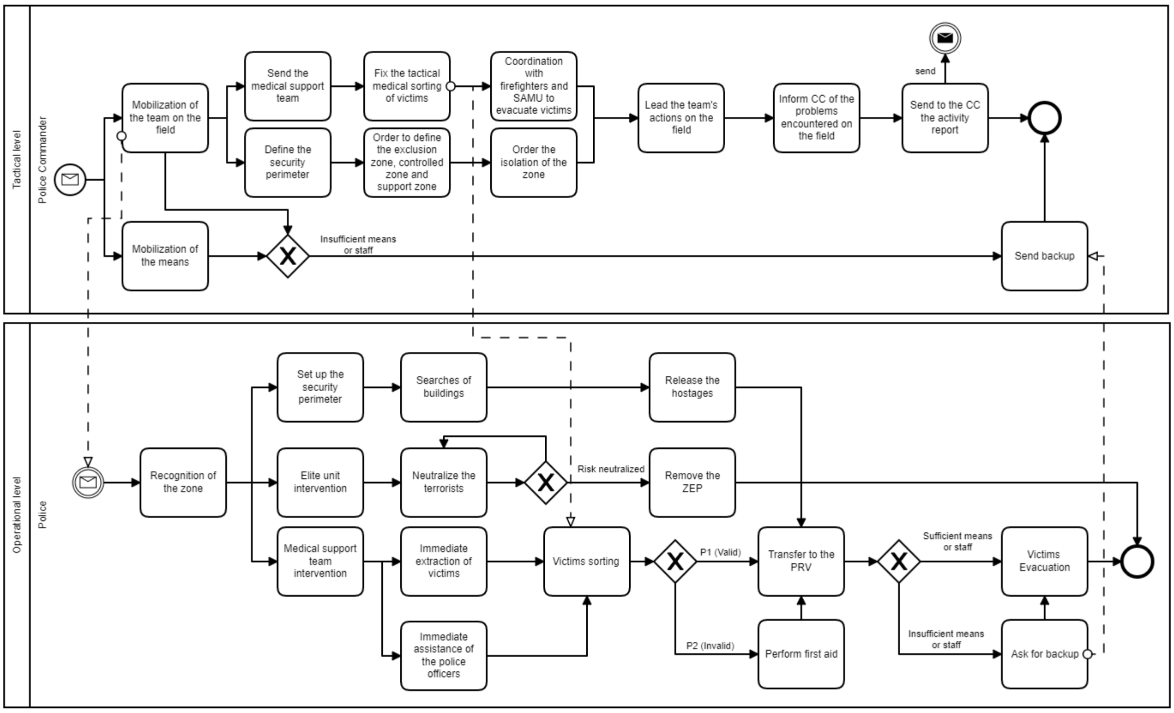

Figure 1.8: The workflow of police forces' process (tactical and operational levels).

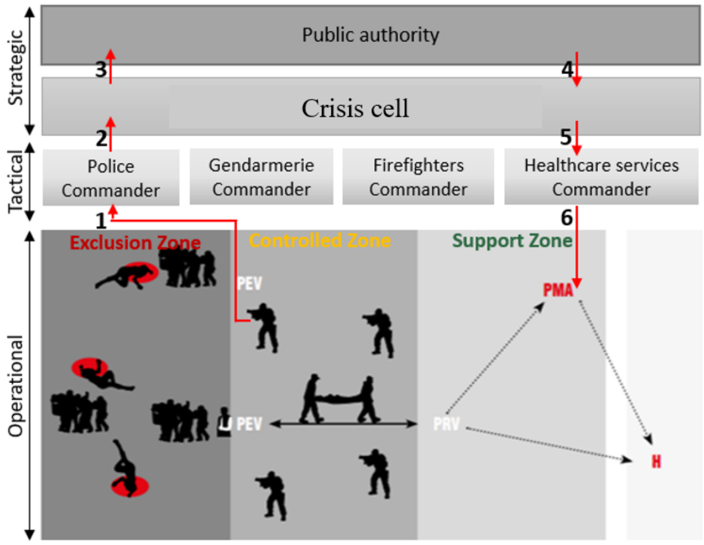

Figure 1.9: Example of information flow among ERs during disaster response.

1.2.1.5 Operational disaster response: Challenges to effectiveness

ERs have been facing a lot of challenges when responding to a disaster. Numerous after-action reports from major disasters have cited communication difficulties among EROs as a major challenge [25] and expressed concerns over the EROs' ability to collaborate. The need for all actors to be able to communicate when responding to a disaster or treating victims is vital. Respectively, communication is a major factor in ensuring effective collaboration during disaster response [8] [26]. But, each ERO has deployed its own information system adapted to its own needs, technical vocabulary, and processes. As a result, information is heterogeneous; in different formats and in different semantics. Semantic heterogeneity of information and the absence of a common language among stakeholders are becoming ever more important issues as the amount of information is growing [8]. These issues lead to misunderstanding and a lack of information sharing among the ERs that can handicap the response process and slow decision making [24].

Moreover, the use of radio communication by each actor makes inter-organizational communication extremely difficult [6]. All too often, the operational actors find themselves during the intervention with poor radio coverage. In a recent survey of EROs (Building Public Safety Communication Survey, 2018), more than 65% of ERs said they had experienced some sort of communication failure within the past twenty-four months while responding to an emergency. Moreover, in the Paris attacks, 2015, firefighters and healthcare units pointed out that the use of radio communication means such as the ANTARES network has not been satisfying during the different interventions [7]. An additional problem is that radio communication does not enable information tractability and consolidation. The availability of technical communication infrastructure has been shown to be a strong predictor of success or failure during disaster response operations [27].

Furthermore, after Hurricane Katrina in 2005, the ERs highlighted the need to have a comprehensive operational picture towards improving the understanding of the situation and facilitating the decision making in order to provide situational awareness. There is a need to provide a common understanding of the needed situational information, how these information are displayed and updated throughout the life of the intervention [28]. To be understandable, an operational picture must consider the terminology and the graphical charter of each ER.

Another important difficulty that ERs face is to find the best allocation of available resources so as to reduce casualties. ERs work together to ensure that those causalities are gathered and transported to an appropriate hospital in a minimum of time. But this process can be more complex if it concerns a multi-site response with limited resources. Hence, resource allocation presents a big challenge for ERs during the operational response.

To summarize, it becomes clear that various factors influence the operational response to disasters. Figure 1.10 recapitulates the keystone challenges that should be considered for an effective multi-agency disaster response. They are related to communication, collaboration, information, and resource allocation. As a result, recognizing the need for enabling interoperability among ERs systems is crucial.

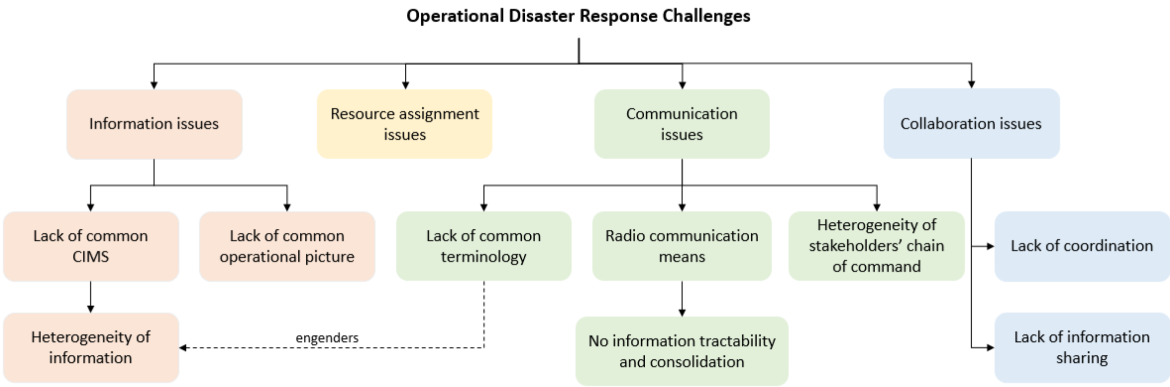

Figure 1.10: Key challenges for the success of the operational disaster response.

1.2.2 Exploring interoperability for operational disaster response

1.2.2.1 Interoperability

There are various definitions of interoperability. For the purpose of this thesis, the three following definitions have been considered. First, interoperability may be defined as the "ability for two (or more) systems or components to exchange information and to use the information that has been exchanged" [29]. Second, it can also be defined as "the ability of two or more software components to cooperate despite differences in language, interface, and execution platform" [30]. Third, Ide and Pustejovsky [31] interpret it as "a measure of the degree to which diverse systems, organizations, and/or individuals are able to work together to achieve a common goal". It can be characterized as a form of system intelligence that enables mutual understanding and enhances cooperation among different information systems. From these definitions, it is possible to decompose interoperability into two distinct types: 'syntactic interoperability' and 'semantic interoperability'. The syntactic interoperability is the ability to exchange information. The semantic interoperability is the ability to use the information once it has been received [32]. Thus, semantic interoperability ensures that these exchanges make sense — that the requester and the provider have a common understanding of the "meanings" of the requested services and data [33].

Interoperability is essential for a successful disaster response. It is considered as the key component that empowers information sharing and the orchestration of the collaborative process in order to build a coherent response to the disaster. It enables ERs to have access to the right information, in the right format, at the right time towards improving collaboration among the involved stakeholders during multi-agency disaster response [34].

1.2.2.2 The Framework of Enterprise Interoperability

Interoperability frameworks aim at structuring and categorizing the concepts of enterprise interoperability research domain. Among these frameworks, one can mention Athena Interoperability Framework (AIF) [35], Interoperability Developments for Enterprise Application and Software (IDEAS) [36], Framework for Enterprise Interoperability (FEI) [37], and European Interoperability Framework for European public services (EIF 2.0) [38]. In the context of this thesis, we adopted FEI in order to highlight interoperability approaches, barriers, and concerns.

FEI was introduced by the European Virtual Laboratory for Enterprise Interoperability (I-VLab) and is now published as an international standard (ISO 11354 - 1) [37]. It defines a classification scheme for interoperability knowledge according to three major dimensions as illustrated in Figure 1.11. First, interoperability can be characterized by concerns. Second, interoperability problems can be localized into interoperability barriers, Third, solutions to interoperability problems can be characterized according to interoperability approaches [39].

Interoperability barriers define the incompatibilities that get in the way of information sharing and exchange. There are three types of barriers: First, conceptual barriers concern syntactic and semantic heterogeneity of information. In this context, syntactic incompatibility means that there are different formats to represent information that prevent them from being combined and accessed. Semantic incompatibility means that there is no defined semantics that enables an unambiguous understanding of the information. In disaster response, each ER requests information in their own vocabulary, data representation, and graphical charter while information is stored in different data sources, with different semantics, and in different formats. Second, technological barriers refer to the incompatibility of information technologies such as the incompatibility of middleware platforms, protocols, and so on. These barriers point to the absence of middleware among the heterogeneous information system used by ERs. Since each stakeholder has deployed his own information system using specific technologies and standards, these latter cannot be interoperable. Third, organizational barriers regard the collaboration of several organizations that wish to exchange information and may have different organizational structures that may create barriers to communication. When the communications channels aren't the same, and stakeholders don't know who to go for what, communication issues can arise.

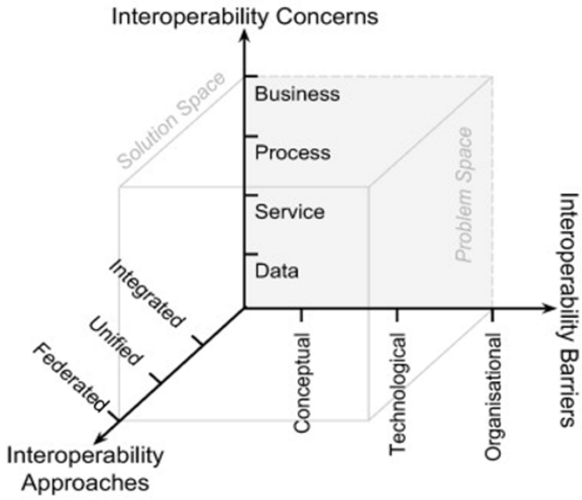

Figure 1.11: The Framework of Enterprise Interoperability (FEI) [40].

Interoperability concerns are four: Data, Service, Process, and Business. First, data interoperability refers to the capability of easily finding, sharing, and understanding data from heterogeneous databases on different machines with different operating systems. Second, the interoperability of service refers to the ability of various independent applications to work simultaneously. Third, the interoperability of process aims to make several processes work together, where a process may be conceived as a sequence of performed services. Finally, the interoperability of business refers to a harmonized way of working across organizations. The interaction among these concerns according to ERs are like the following; data (different semantics, in different formats, and stored in different databases of ERs) is employed by services (different functions and roles of each stakeholder) and services are used by processes (coordination of ERs' processes of intervention) to perform business (multi-organizational response to a disaster).

Enabling interoperability among systems is not only a matter of removing barriers; it also matters how these barriers are removed [41]. There are three ways in which barriers can be removed: First, the integrated approach refers to the use of a common format (standard) for all models. It concerns the integration of systems more than the interoperability of systems. Second, the unified approach signifies that there is a common format only at a meta-level. It establishes semantic equivalence among information in order to enable the mapping between models. But, this may engender the loss of some semantics. Third, the federated approach holds that there is no imposed format at all but, instead, there is a shared ontology.

To sum up, each intersection among a concern, a barrier, and an approach is an interoperability research area. The different interoperability solutions proposed in the literature may be positioned into the FEI to highlight the studied interoperability barriers and concerns, and the corresponding approaches.

1.2.2.3 Study of existing crisis information management systems

In the literature, research efforts have focused on improving disaster management by developing crisis information management systems (CIMSs). There are other terms used to describe software systems of this sort, such as disaster management interoperability systems and critical incident management systems. However, CIMS is the term most commonly used across multiple agencies and jurisdictions where information exchange and sharing and coordinated actions are required [42].

A CIMS is a computer-based software system that facilitates storing, organizing, and analyzing information, managing resources, supporting a common operational picture, maintaining command and control, and facilitating decision making and collaboration among multiple organizations in order to aid in orchestrating response efforts and sharing of information [43]. CIMSs are used to deal with both day-to-day emergencies as well as large-scale disasters. They aim to provide a suite of information communication technology (ICT) functions to address the needs of stakeholders involved in the disaster management process. When designing a CIMS, interoperability is a key component of its success.

To achieve interoperability among disaster response actors, a variety of research avenues have been proposed in the literature. They focus on one or more aspects of the aforementioned challenges of the operational disaster response that need to be resolved to ensure information sharing and reliable communication for coordinated interventions [17]. Among these, we identified two related research questions:

- Is a given proposed CIMS sufficiently interoperable?
- Does this CIMS meet the challenges of effective disaster response?

We analyze several recent projects, namely SECTOR, DISASTER, DESTRIERO, SecInCore, DRIVER, DARWIN, IsyCri, GéNéPi, SOKNOS, RESCUER, LDDRS, ERMS, AFDM, BRIDGE.

In [44], the authors proposed a CIMS as part of the project SECTOR (Secure common information space for the interoperability of first responders). It is an EU-funded project that started in 2014. Authors proposed not a single unique system for all the ERs, but a common information space (CIS) that provides users “peer-to-peer” functionalities to dynamically establish cross-agencies and cross-borders collaborative platform. That is to say, by means of the proposed CIS, the authors established a unified approach to enable interoperability among multi-organizations systems by removing conceptual and technological barriers. From an operational point of view, this work focused only on decision making within disaster response organizations in order to optimize the process of resource allocation.

The European project DISASTER (Data Interoperability Solutions at STakeholders Emergencies Reaction) seeks to solve the task of information sharing and coordination among international workforces in order to ensure interoperability among different CIMS [45]. The authors proposed a software application that mediates communication among different CIMS. To support the mediation and to provide organizations with the needed information, DISASTER is based on a common modular ontology named EMERGEL that considers the linguistic, semantic, and cultural differences among countries. This work followed a federated interoperability approach and proposed an ontology that will be used in translating emergency-related terms in cross-border disaster response. They tried to remove conceptual and technological barriers to ensure interoperability among data and services. Furthermore, the DISASTER project focuses mostly on the strategic level of disaster response in cross-border situations. The DISASTER project underrepresents information sharing and collaboration among operational ERs on the disaster site. Moreover, the semantic mapping of information is left out and end-user requirements were not identified.

In [46], the authors propose a CIMS named DESTRIERO (A DEcision Support Tool for Reconstruction and recovery and for the IntEroperability of international Relief units in case of complex crises situations, including CBRN contamination risks). It is a middleware platform for messaging, knowledge management, and data transformation in large-scale disasters. To ensure interoperability, DESTRIERO pursues a federated interoperability approach by proposing a standard-based formal ontology in order to remove conceptual and technological interoperability barriers by resolving technological, syntactical and semantic heterogeneity of information occurring among organizations. Despite this proposal, from an operational point of view, the proposed CIMS architecture provided a tool for information exchange among actors at the tactical level of disaster response, and it fails to represent the graphical charter that signate ERs' vocabularies to represent what is happening exactly on the disaster site. Moreover, there is no real prototype of the proposed architecture.

In the European project SecInCoRe (Secure Dynamic Cloud for Information, Communication and Resource Interoperability based on Pan-European Disaster Inventory), the authors introduce a CIS [47]. As part of their design process, the authors conducted a Pan-European inventory of disasters and their consequences. They then elaborated a dynamic cloud-based communication system concept. The authors proposed a federated interoperability approach by proposing a shared ontology created by reusing vocabularies, glossaries, and semantic approaches, although the proposed CIS focused on enabling interoperability only among first responders and police forces.

The SoKNOS project proposes a prototype of an ontology-based CIMS for creating a mutual understanding between developers and end-users across different organizations [48]. In fact, information sources and services are annotated with ontologies in order to connect existing systems and databases to the SoKNOS system. Hence, SoKNOS focuses on ensuring conceptual interoperability of data by proposing a federated approach by using an ontology to formalize the knowledge of the heterogeneous organization involved in the process of disaster management. However, they did not consider all the involved ERs (only firefighters and police forces) and their technical vocabulary.

DRIVER project (Driving Innovation in Crisis Management for European Resilience) proposes a distributed Pan-European test-bed to provide guidelines on how to perform experiments as well as a framework to evaluate the results [49]. It suggests communication solutions among disaster response managers and citizens (or unaffiliated volunteers). DRIVER is also related to other projects, such as DARWIN2, which aims to provide emergency responders guidelines so as to facilitate disaster response. To summarize, DRIVER and DARWIN2 both propose integrated interoperability approaches to remove technological barriers of data and services among stakeholders and volunteers. However, the experiments of these projects have clearly demonstrated technological shortcomings that need to be addressed. Moreover, this work does not resolve the deficiency of communication and coordination among operational stakeholders. However, these challenges are the key to a successful disaster response.

IsyCri is a French project that provides an information system in order to enable interoperability among the actors responsible for the reduction of disaster situations [50]. To accomplish this task, the strategy is to merge the information systems of the different involved stakeholders into a global system. The authors tried to remove technological and organizational barriers by proposing a unified interoperability approach. The IsyCri project focuses more on meta-ontologies to structure and formalize concepts related to disaster response. In fact, meta-ontologies are equivalent to the meta-model of a modeling language that encapsulates the concepts that will be used for creating domain ontologies. We conclude that this information system targets the orchestration of the collaborative process of the strategic level of disaster response and does not resolve the highlighted challenges of inter-services operational response.

In the same context, [51] propose the generation of collaborative processes in the crisis management field as part of the Génépi project. It attempts to improve disaster response by supporting stakeholders' collaboration on the field and decision-making in the crisis cells. More accurately, on the one hand, it generates a model that illustrates the crisis situation on the field so that the crisis cell could follow the situation's evolution. On the other hand, it recommends a set of strategies of coordinated activities copying with the observed facts to support the crisis cell in decision-making. This work ensures the interoperability of data and processes using a unified approach.

The RESCUER project (Reliable and Smart Crowdsourcing Solution for Emergency and Crisis Management) proposes a smart interoperable CIMS that supports a disaster response command center [52]. Its focus is on incidents in industrial areas and large-scale disasters. It gathers and manipulates information provided by people from the incident area to create data visualizations. This system is addressed to the strategic level of disaster response in order to collect relevant missing contextual information about the disaster from eyewitnesses and then communicate instructions to the affected people, ERs, public authorities, and also the press. To do so, the work proposes a federated approach, an ontology-based data-exchange solution to allow semantic interoperability between RESCUER and the command center [53]. The ontology is defined on the basis of the Emergency Data Exchange Language (EDXL). However, EDXL-RESCUER does not cover information exchange among ERs on the disaster site.

Vidan and Hogan [54] have been working on a prototype command and control system, LDDRS (Lincoln Distributed Disaster Response System), that enables shared situational awareness and collaboration during response operations. In LDDES, an integrated interoperability approach is proposed to display a map of an area of interest in order to locate staff and vehicles. LDDES provides a real-time common operational picture accessible to all ERs but it doesn't consider the details of what is happening on the scene. It shows only the position of vehicles and staff.

Authors in [55] propose a cloud-based digital platform to be used by the emergency agencies and the citizens in the context of the French project NexSIS 18-112. It aims to enable real-time reporting of crisis management at higher levels capable of offering instant messaging, and real-time text (RTT), voice, and video services to emergency stakeholders. In addition, the focus is to receive information flows produced by social networks and integrated them into the platform. However, this project is still a work in progress and there are no published results.

In [56], authors present a cross-organizational middleware in the context of the AFDM (Algerian Framework for Disaster Management) project. The objective is to integrate data from different stakeholders' systems in order to ensure real-time map-based visualization and decision support based on the integrated information. The proposed middleware acts as a central system on the top of stakeholders' information systems. To implement the service integration component, the common set of technologies for web services such as XML (Extensible Markup Language), UDDI (Universal Description, Discovery, and Integration), WSDL (Web Services Description Language), SOAP (Simple Object Access Protocol) have been used. However, the integrated data visualized on the map concerns only sectoral risks. In terms of interoperability, authors propose an integrated approach to resolve technological barriers concerning data.

The European project BRIDGE (Bridging Resources and Agencies in Large Scale Emergency Management) proposes a middleware that integrates stakeholders' data sources, networks, and systems [57]. It plays the role of a bridge between multiple emergency responders organizations. The focus is on interoperability of data by providing technical and organizational solutions in order to improve emergency management and to ensure harmonization among the involved stakeholders. It offers a set of services including data management, messaging, security, trust, and so on. In spite of that, the BRIDGE project does not consider the heterogeneity of semantics among stakeholders.

An emergency resource management system (ERMS) is proposed in [58] for the use in day-to-day emergencies as well as during crisis response. ERMS employs geographic information, internet of things, and cloud technologies for real-time management of resources. ERMS promotes data interoperability by proposing an integrated approach to solve technological barriers. It determines the availability of the needed resources and how they can be delivered to the emergency scene. The resources' requirements are considered based on the study of historical cases and the estimation of the crisis impacts. Moreover, the cloud platform provides users the possibility of resource tracking using global positioning system (GPS) locators of the vehicles.

Table 1.1 and Table 1.2 summarize the comparisons of CIMSs proposed by the previous highlighted projects in terms of interoperability approaches, concerns, and barriers as well as operational challenges.

Table 1.1: Comparative study of existing CIMSs basing on the Framework of Enterprise Interoperability.

Projects	Approaches			Barriers			Concerns				Literature
	Integrated	Unified	Federated	Conceptual	Technological	Organizational	Data	Service	Process	Business	
SECTOR	×	✓	×	✓	×	×	✓	✓	×	×	[44]
DISASTER	×	×	✓	✓	✓	×	✓	✓	×	×	[45]
DESTRIERO	×	×	✓	✓	✓	×	✓	×	×	×	[59]
SecInCore	×	×	✓	✓	✓	×	✓	×	×	×	[47]
DRIVER	✓	×	×	×	✓	×	✓	✓	×	×	[49]
DARWIN	✓	×	×	×	✓	×	✓	✓	×	×	[49]
IsyCri	×	✓	×	×	✓	✓	✓	✓	✓	✓	[50]
GéNéPi	×	✓	×	×	✓	✓	✓	✓	✓	×	[51]
SOKNOS	×	×	✓	✓	×	×	✓	✓	×	×	[48]
RESCUER	×	×	✓	✓	×	×	✓	×	×	×	[52]
LDDRS	✓	×	×	×	✓	×	✓	✓	×	×	[54]
AFDM	✓	×	×	×	✓	×	✓	×	×	×	[56]
BRIDGE	✓	×	×	×	✓	✓	✓	×	×	×	[57]
ERMS	✓	×	×	×	✓	×	✓	×	×	×	[58]

Table 1.2: Comparative study of existing CIMSs basing on the operational response challenges.

Projects	Communication	Information sharing	Common terminology	Common CIMS	Operational picture	Resources allocation	Literature
SECTOR	×	✓	×	×	×	✓	[44]
DISASTER	✓	×	✓	✓	✓	×	[45]
DESTRIERO	✓	×	✓	×	×	×	[59]
SecInCore	✓	✓	✓	×	×	×	[47]
DRIVER	✓	×	×	×	×	×	[49]
DARWIN	✓	×	×	×	×	×	[49]
IsyCri	×	×	×	✓	×	×	[50]
GéNéPi	×	✓	×	×	✓	×	[51]
SOKNOS	×	×	✓	×	×	×	[48]
RESCUER	✓	×	✓	×	×	×	[52]
LDDRS	×	×	×	×	×	×	[54]
AFDM	×	×	×	✓	✓	✓	[60]
BRIDGE	✓	×	×	✓	×	×	[57]

1.2.2.4 Discussion

This review makes clear that despite the huge work done, there is still a great need to improve CIMSs for disaster response. We have noticed that there is no CIMS that considers all the challenges of disaster operational response. Moreover, there are interoperability concerns (process and business) and barriers (conceptual and organizational) that are most of the time neglected despite their major importance and their impacts on disaster response.

On the one hand, organizational barriers were disregard by the studied CIMSs as seen in Table 1 because the focus of these latter is mainly on the strategic level of disaster response. Indeed, organizational barriers should be considered in operational disaster response given that the hierarchical chain of command and the nature of the involved actors vary from one organization to another. The organization structure itself created barriers to communication. Thus, the absence of knowledge of structure, policies, and procedures of the other party impede communication [61]. When the channels of communications aren't the same, and stakeholders don't know who to go for what, communication issues can arise. For instance, all communications regarding resource allocation flow back to a department of communication in organization A, but within organization B, the department of communication does not receive such communications; rather they go directly to an emergency dispatch. That is, a good understanding of the hierarchical chain of command of each ERO can greatly impact information flow and decision making. Accordingly, the consideration of organizational barriers will eliminate the confusion caused by several and conflicting commands. Each stakeholder fulfilling a role should have a clear route of communication up and down the chain of command.

On the other hand, conceptual barriers are disregarded by most of the studied works while they present a key factor in successful information exchange among stakeholders. Yet, each ERO has its own specific area of expertise, technical vocabulary, and terminology. As a direct result, ERs could encounter misunderstanding that can make the response process slow, failing, and inefficient. One word may be interpreted differently from one context to another. Accordingly, semantic heterogeneity should be considered to ensure the efficiency of communication among stakeholders and enable collaboration of multi-agencies disaster response.

Afterward, Process and business are two major concerns that should be considered when addressing interoperability requirements. Together, they represent the orchestration of stakeholders' actions within different organizations and their collaborations in a coordinated and harmonized manner.

Various CIMSs have proposed the use of a federated approach to overcome semantic heterogeneity of information among stakeholders. However, there is still a lack of semantic interoperability among the involved stakeholders. We believe that the development of common terminology is essential to guarantee a consistent shared understanding of the meaning of information to be exchanged. Considering that each ERO has its own vocabulary, process of intervention, acts and so on, in this thesis, we used the federated approach to establish interoperability "on the fly" (see Figure 1.12). That is, interoperability accommodation should not impose the existing models, languages, and methods of work as the common format. Consequently, each ER maintains control over their own information and is capable of working with the rest of the stakeholders according to a set of collaborative processes that have a common objective. Accordingly, in this work, we intend to resolve conceptual, technological, and organizational barriers (see Figure 1.13) by developing an ontology-based system that considers the semantic terminology of each ER.

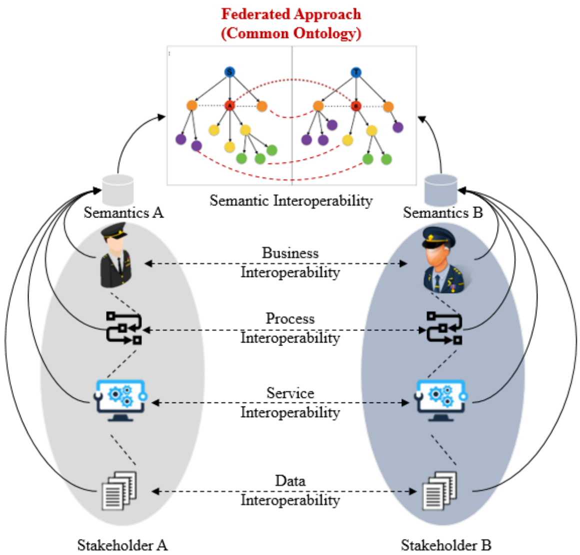

Figure 1.12: The studied interoperability approach and concerns [62].

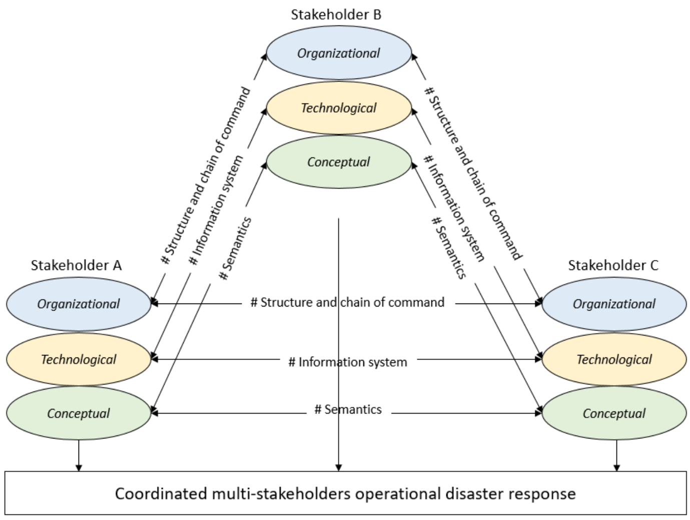

Figure 1.13: The studied interoperability barriers.

1.2.3 Exploring ontologies for operational disaster response

In the following, we present some backgrounds about ontologies and a study of the existing ontologies proposed in the context of disaster response.

1.2.3.1 Distinction between data, information, and knowledge

The distinction between data, information, and knowledge remains typically vague. These terms are used extensively, often in an interrelated context. They indicate different levels of abstraction (see Figure 1.14). Data is about different symbols and characters that are raw and without context. It can exist in any form, usable or not. Once data are connected to a context, it becomes information. More accurately, information is a set of processed data that have meaning. Knowledge is derived from the information as well as information derived from the data. The combination of information understanding and capability results in knowledge [63]. In the literature, we have seen an explosion of interest in using ontologies in the organization, contextualization, and representation of knowledge [64].

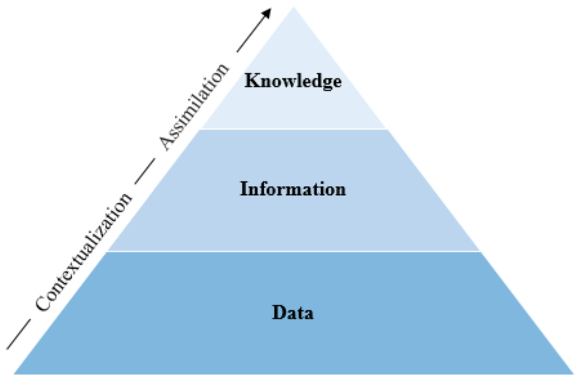

Figure 1.14: From data to knowledge.

1.2.3.2 What is an ontology?

The term Ontology (or ontologia) is one of the oldest forms of philosophy. It is generally what we called before Aristotle's general metaphysics. It is the study of what is, of the kinds and structures of objects, processes, properties, and relations in every area of reality [65]. In computer and information science, an ontology is defined as an "explicit specification of conceptualizations for a certain domain of interest" [10]. In [15], Studer et al. defined an ontology as a "formal, explicit specification of a shared conceptualization". In fact, conceptualization can be viewed as an abstract and simplified view of the world that we wish to represent; concepts that exist in some area of interest, their specifications, and the relationships that can hold between them [66]. Ontologies are expressed in a logic-based language, so that accurate, consistent, and meaningful distinctions can be made among classes, instances, properties, attributes, and relations to reveal the implicit and hidden knowledge in order to understand the meaning of the data.

There are various reasons for developing ontologies [67]:

- Knowledge sharing: the use of ontology enables the share of a common understanding of knowledge among people, or software agents.
- Knowledge reuse: one can create an ontology without starting from scratch by integrating existing ontologies.
- Logic inference: ontologies can be exploited by several logical reasoning mechanisms to deduce hidden knowledge and to check its consistency.

Ontologies have been identified as an effective means to implement semantic integration and to achieve information interoperability. They offer the richest representations of machine-interpretable semantics for systems and databases [68]. They serve as both knowledge representation and as mediation to enable heterogeneous systems interoperability. Thus, to overcome semantic heterogeneity and to guarantee a consistent shared understanding of the meaning of information, the use of ontologies is crucial [69].

1.2.3.3 Ontology structure

The main components of an ontology are classes, relations, instances, and axioms [70]:

- Classes represent kinds of things within a certain domain of interest and their properties. It can be about an object, task, action, process, etc. There are two types of classes primitive or defined. Primitive classes have a set of necessary conditions (e.g. superclasses). Defined classes have a set of necessary and sufficient restrictions (e.g. equivalent classes).
- Relations specify the interactions between classes and how they are connected to each other. There are two types of relations; taxonomies relations organize a set of classes into a subclass tree structure using the relationship “is a”, and associative relations connect the classes across the tree structure (for example “connected to”). Relations also can exist between instances.
- Axioms specify the knowledge of the domain that is always true.
- Instances are individuals that respond to the classes’ intension.

1.2.3.4 Ontology’s levels of abstraction

There are three main levels of abstraction of ontologies specifically upper, mid-level, and domain ontologies as illustrated in Figure 1.15.

First, the upper-level ontology, as defined in [71], "describes very general concepts that are the same across all domains and usually consist of a hierarchy of entities and rules (both theorems and regulations) that attempt to describe those general entities that do not belong to a specific problem domain". They provide a high-level domain-independent conceptual model that describes abstract concepts such as objects, processes, events, and quality. Second, mid-level ontology presents the bridge between the abstract concepts of upper-level ontologies and the rich details of domain ontologies by adding more specific modules like space and time. Third, domain ontologies or lower ontologies describe concepts of a domain of interest in a very specific way and it may also extend concepts from mid-level ontologies. There is another kind of ontology called domain reference ontology which is richer than a mid-level ontology since its aim is to make the best possible description of a domain in reality and less specific than domain ontology since it does not cover specifies of the domain but rather it provides a clear understanding of the common terms. The main benefit of the use of reference ontology is to promote semantic interoperability between domain ontologies [72].

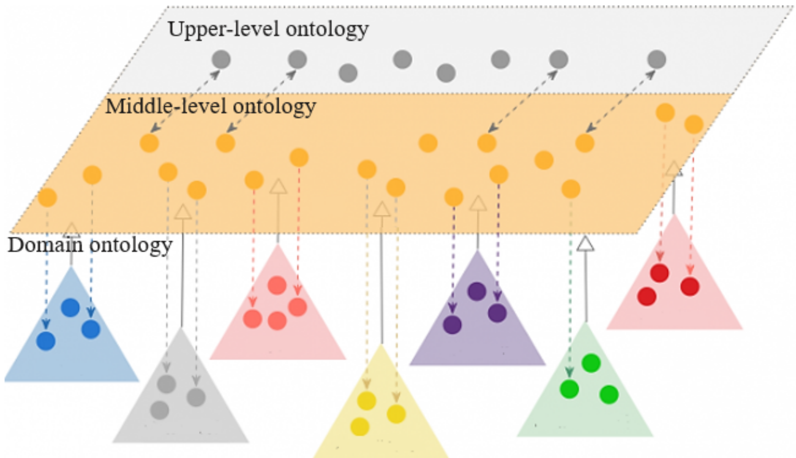

Figure 1.15: Ontology's levels of abstraction.

1.2.3.5 Study of upper-level ontologies and their usability

Over the years, several upper-level ontologies have been already developed and well established.

Cys project [73] was founded in 1984 by D. Leant as a lead project in the Microelectronics and Computer Technology Corporation (MCC). The aim of Cyc ontology is to enable the usage of knowledge across domains. The ontology includes a wide range of categories. The fundamental distinction of entities in the ontology is between collections and individuals. It captures concepts such as temporality, mathematics, and relationship types.

GFO (General Formal Ontology) [74] project was launched in 1999 in the context of GOL project (General Ontological Language) at the University of Leipzig. It is an upper-level ontology presenting a multi-categorial approach that integrates universals, concepts, and symbol structures and their interrelations. It contains several novel ontological modules, in particular, a module for functions and a module for roles. It exposes a three-layered meta-ontological architecture consisting of an abstract top-level, an abstract core level, and a basic level.

SUMO (Suggested Upper Merged Ontology) [75] is an upper-level ontology developed in 2000 by the Standard Upper Ontology Working Group, an IEEE-sanctioned working group composed of researchers from different fields such as engineering, philosophy, and information science. It proposes definitions for general-purpose terms as a foundation that intends to be expanded for more specific domain ontologies. The idea of SUMO was the merging of several existing upper ontologies that did not have licensing restrictions, including John Sowa's upper-level ontology, Russell and Norvig's upper-level ontology, James Allen's temporal axioms, Casati and Varzi's formal theory of holes, Barry Smith's ontology of boundaries, Nicola Guarino's formal mereotopology, and various formal representations of plans and processes. Indeed, SUMO is a mixed upper ontology that contains both elements of realism as well as cognitively specific categories [76].

BFO [77] project was initiated in 2002 under the auspices of the project Forms of Life sponsored by the Volkswagen Foundation. It is designed for use in supporting information retrieval, analysis, and integration in scientific and other domains. It doesn't contain specific terms such as physical, chemical or biological terms. BFO is a realist, formal and domain-neutral upper-level ontology, it is designed to represent at a very high level of generality the types of entities that exist in the world and the relations that hold between them. It is utilized as a starting point for the categorization of entities and relationships by more than 300 domain ontology.

DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) [78] is the first module of a Foundational Ontology Library for the Semantic Web being developed within the WonderWeb project19 that started in 2002. It is not intended to be a universal or standard upper ontology, but instead, it serves as an ontology of instances. The most fundamental distinction between entities made in DOLCE is related to their behavior in time. On one hand, «Perdurants» are entities that unfold in time, on the other hand, «Endurants» are entities that are present 'all-at-once' in time.

COSMO (Common Semantic Model) [79] project started in 2006, it arises from the efforts of the COSMO working group (COSMO-WG) and its parent group, the Ontology and Taxonomy Coordinating Working Group (ONTACWG). It is the result of merging some upper-level ontologies. COSMO integrates concepts from the Cyc project, SUMO ontologies, DOLCE, and BFO.

Reusing well-established ontologies in the development of a domain ontology allows one to take advantage of the semantic richness of the relevant concepts and logic already built into the reused ontology. In this way, ontologies may provide a web of meaning with a semantic decomposition of concepts [80]. In addition, the use of upper-level ontologies facilitates the integration of several domain ontologies. In other words, if the ontologies to be mapped are driven from a stander upper-level ontology, this will make the mapping task easiest. In addition, upper-level ontologies play the same role as libraries in software programming tasks. Once they are used, one could reuse the defined concepts and relationships and inherit the inferencing capabilities furnished by them. In this way, developing a domain ontology is an easier task that requires less time than usual. Moreover, the aim is to avoid having several incompatible domain ontologies. The usage of upper-level ontologies for integrating information and sharing knowledge among heterogeneous sources has been motivated in various related works [81]. Moreover, they have been used in various domains including situation awareness, pervasive systems [82], biomedical information systems, and disaster management systems [80].

1.2.3.6 Distinction between ontology, meta-model, and model

There has been a continuing confusion between the terms ontology, meta-model, and model. According to [83], a model is a set of elements that describe some physical, abstract or hypothetical reality. It is a simplified representation of a certain reality [84]. Clark, et al. [85] define a meta-model as “a model of a model which captures a particular domain’s essential properties and a list of relevant relationships between these concepts”.

Whereas, ontologies offer the richest representations of machine-interpretable semantics for systems and databases [68]. Foundational or upper-level ontology provides general concepts for domain ontologies. In other words, an upper-level ontology may be used at the same abstraction level as a meta-model, and a domain ontology at the same abstraction level as a model [86] [87] (see Figure 1.16).

An ontology could be associated to a meta-model. In fact, there are two types of ontologies according to [86];

- Domain ontology deals with real-world descriptions of a specific domain application.
- Méta-ontology encapsulates the concepts needed for creating domain ontology.

1.2.3.7 Ontology building methodologies

To build an ontology, a methodology that guides and manages the development process is key. In fact, the utility of an ontology depends entirely on its development methodology. An ontology development methodology comprises a set of established principles, processes, practices, methods, and activities used to design, implement, evaluate, and deploy ontologies [88]. In order to assist researchers and domain experts in building ontologies, to date, several ontology-building methodologies have been proposed in the literature.

METHONTOLOGY was developed within the Ontological Engineering group of the Laboratory of Artificial Intelligence at the Polytechnic University of Madrid. It is one of the most famous ontology building methodologies. It is a structured set of activities to build

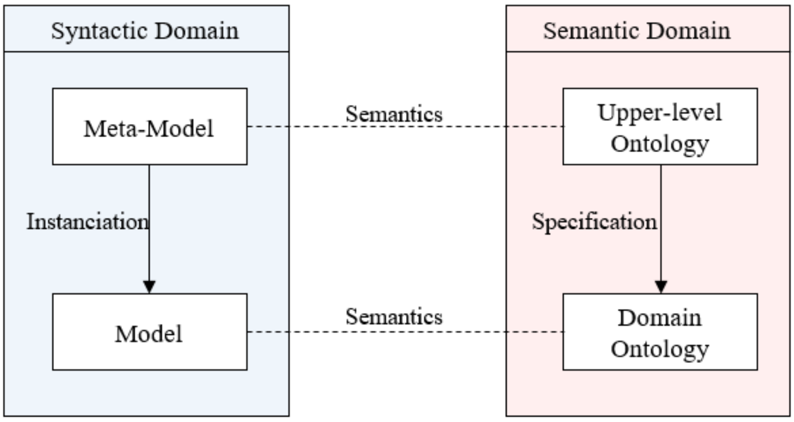

Figure 1.16: The relationship between ontology, meta-model, and model.

ontologies from scratch. Its framework enables the construction of domain ontologies at the knowledge level and following a life cycle based on involving prototypes and techniques [89].

NeOn methodology was proposed within the NeOn project for building ontologies and ontology networks. It is a scenario-based methodology that enables the collaborative aspects of ontology development and the dynamic evolution of ontology networks. The aim of this framework is to accelerate the process of construction of the ontology by reusing available knowledge resources (ontological and non-ontological resources). NeOn is based on a set of nine flexible scenarios and two life cycle models [90].

OTK methodology was developed within the On-To-Knowledge project in order to be used in application-driven development of ontologies. The focus is on proposing a new process based on human issues, where domain experts that are not familiar with modeling are capable of building their own ontology [91].

AFM (Activity-First Method) methodology is used in the development of task and domain ontologies from technical documents [92].

TOVE (Toronto Virtual Enterprise) methodology was proposed to support enterprise process modeling at Toronto university. Its first step is to define a motivating scenario that presents an initial description of the informal intended semantics that an ontology should cover. Moreover, it focuses on formal techniques of maintenance in order to address a limited number of maintenance issues [93].

DILIGENT methodology is proposed for the collaborative development of ontologies by several domain experts and ontology engineers with different and complementary competencies [94].

OntoClean methodology was first introduced in 2000 and is based on a formal foundation of philosophical notions for ontological analysis [95].

1.2.3.8 Study of existing ontologies and meta-models for disaster response

In the literature, different types of ontologies and meta-models have been proposed to define terms related to disaster response. The existing ontologies and meta-models are reviews based on the covered information in the field of disaster response including disasters, stakeholders, victims, roles, processes, resources, and so on.

The EMERGEL ontology, proposed in the context of the DISASTER project [45], mainly focuses on the mapping of different pre-defined information artifacts, information representation, and language among countries in Europe. It reuses the class event from the upper-level ontology DOLCE and other vocabularies such as FOAF (Friend Of A Friend) [96] that is used to model people in an emergency situation. It is composed of vertical modules that represent the various stakeholders (fire domain, health domain, etc.) and two horizontal modules that represent time and space. The ontology mapping is used to perform specific translations between stakeholders from different countries. However, this ontology lacks specific operational information (such as the technical vocabulary of each ER). It can be more useful in decision making at the strategic level rather than the operational level.

OntoEmergePlan is a domain ontology that defines emergency plans. It aims to support models and systems that focus on the systematic generation of emergency plans. It is developed considering the analysis of emergency management processes from England, Australia, USA. It defines mainly emergency processes and activities, resources, roles, and environment [97]. However, it does not cover all the operational vocabularies of ERs.

The EDXL-RESCUER ontology [53] is the conceptual model of RESCUER project. It uses EDXL (Emergency Data Exchange Language) standards to model the coordinating and exchanging of information with legacy systems. In fact, EDXL standards are developed by OASIS (Organization for the Advancement of Structured Information Standards). The focus of EDXL-RESCUER is mainly on alerting people. It is composed of four ontologies; one ontology for each EDXL package namely, EDXL-DE (distribution element), EDXL-RM (resource messaging), EDXL-CAP (common alerting protocol), and EDXL-SitRep (situation reporting).

Another ontology that used EDXL standards as a basis is PS/EM Communication ontology (Public Safety and Emergency Management) [98]. It is proposed in the context of the IDA project (Institute for Defense Analyses). To develop the ontology, authors were based on three EDXL standards; messaging distribution element, hospital availability exchange, and common alerting protocol. The ontology is constructed by adding specializations to the upper-level ontology BFO and the mid-level ontologies CCO classes. However, this ontology does not cover all types of communication among ERs; it is focused only on alert messages.

ResOnt is provided in [99] for representing situations during rescue operations in order to support situations awareness. It aims to support French first responders in data interpretation during rescue operations. ResOnt is based on the upper –level ontology SUMO and reuses classes from existing ontologies such as EMERGEL. Mainly, it defines events, resources, and tasks. However, the proposed ontology is not evaluated and implemented yet. In addition, it is dedicated only to firefighters and healthcare staff and to be used just in day-to-day emergencies. ResOnt does not cover the operational vocabulary of the French stakeholders.

In the same context, authors in [100] provide BFER (Building Fire Emergency Response) domain-model. It describes the knowledge that can be used by firefighters inside the building during rescue operations. The domain model consists of four components; an event component that contains elements that describe the building fire emergency characteristics (e.g. date, time, area), an actor component that define responders' properties and tasks, an objective component that contains the goals to fulfill, and a building component that depicts the characteristics of the building (e.g. building type, access facility). Nevertheless, BFER domain-model does not consider the operational processes of stakeholders.

In [101], authors focus on knowledge related to firefighters and propose emergency fire (EF) ontology. EF defines fire incidents, building features, resources and response actions. Moreover, it formalizes protocols used in tactical and strategic planning.

Haghighi et al. [102] propose DO4MG (Domain Ontology for Mass Gatherings) that specifically describes the domain knowledge for planning and managing medical services in mass gatherings. It also represents medical resources' allocation in emergency management. The main classes of DO4MG are mass gathering, gathering type, mass gathering plan, event venue, crowd feature, and environmental factors.

Santos et al. [103] suggest a meta-model for handling infrastructure-related adverse events called BFiaO (Basic Formal infrastructure incident assessment Ontology). But, it did not provide models for a catalog of adverse events and the needed means for an adequate response.

Authors in [104] look for solving the problem of spatial data heterogeneity in emergency situations and their transmission to stakeholders. To do so, they propose an emergency management ontology (EMO) by using a dynamic data model and various existing data sets. The ontology is composed of two parts; a static data ontology and a dynamic data ontology (e.g. hydrology ontology and meteorology ontology). Moreover, authors propose separate domain ontologies that define stakeholders' knowledge that are linked to the emergency management ontology.

Concerning SoKNOS ontology [48], it includes resource planning, damages, and geo-sensor information. It is a core domain ontology on emergency management aligned to the upper-level ontology DOLCE. It imports a set of ontologies including resources ontology, damage ontology, and geo-sensor discovery ontology. The aim is to categorize damages, resources, and the relations between them.

The authors of [105] put forward a meta-model and its corresponding ontology web language (OWL) in the context of the project ISyCri (Interoperability of Systems in Crisis Situations) in order to define the generic dimensions of crisis characterization through an adequate collaborative process.

In [106], an emergency response ontology (ERO) based on a generic emergency response workflow is provided. It defines knowledge of four major phases; response preparation, emergency response, emergency rescue, and aftermath handling. The aim is to standardize a set of generic semantic concepts related to the four mentioned phases. But, concerning the emergency response and rescue phases, it includes only stakeholders dispatch on the emergency scenes and their roles (e.g. evacuation, medical aid, scene control, monitor and alert). The proposed ontology is too general to be used in the operational disaster response.

In the same context, a generic and domain-independent disaster management metamodel is presented in [107]. It defines common concepts that exist in many other disaster management models into four different classes of concepts; mitigation, preparedness, response, and recovery.

Gaur et al. [108] propose an ontology for emergency managing and planning about hazard crisis (Empathi). It is based on the automatic recognition of disaster concepts mentioned in social media conversations. It defies hazard situational awareness and events and their impacts on the affected population and infrastructure. It is linked to different vocabularies including FOAF that describes people and associated events, LODE (Linked Open Descriptions of Events) that defines events, and so on.

Other ontologies like MOAC (Management of Crisis vocabulary) [109] and HXL (Humanitarian eXchange Language) [110] define crisis types, damages, response activities, and resources. HXL is proposed by the united nations office for the coordination of humanitarian affairs. It aims to contribute to the automatization of the data exchange process for disaster response. Specifically, it focusses on improving information flow among decision-makers during resource allocation. To do so, the HXL vocabulary provides a formal definition of this domain.

Bannour et al. [111] present CROnto (Crisis Response Ontology) that defines crisis features, crisis effects, and crisis response. It formalizes mainly disasters, their damages, resources, and organizations. It is expected that the proposed ontology will be exploited by an intelligent decision support system in order to improve crisis management and to suggest real-time strategic response plans. Moreover, the focus is on contributing to strategic planning more than operational response.

Table 1.3 summarizes the comparison of the studied ontologies and meta-models in terms of the covered knowledge of the disaster response process.

Table 1.3: Comparative study of existing disaster management ontologies.

Ontology	Disasters	People	Organization	Roles	Processes	Resources	Time and space	Communication	Literature
EMERGEL	✓	×	✓	×	×	✓	✓	×	[45]
OntoEmergePlan	×	×	✓	✓	✓	✓	×	×	[97]
SoKNOS	×	×	×	×	×	✓	×	×	[48]
EDXL-RESCUER	×	×	×	×	×	×	×	✓	[53]
ResOnt	×	×	✓	✓	×	✓	×	×	[99]
EMO	×	×	✓	×	×	✓	✓	×	[104]
ISyCri	✓	×	×	×	✓	×	×	×	[105]
PS/EM	×	×	×	×	×	×	×	✓	[98]
BFER	×	×	✓	✓	×	✓	✓	×	[100]
EF	×	×	✓	×	✓	✓	×	×	[101]
DO4MG	×	×	×	×	×	✓	×	×	[102]
BFiaO	✓	×	×	×	×	✓	×	×	[103]
ERO	×	×	✓	×	×	×	×	×	[17]
Empathi	✓	✓	×	×	×	×	×	×	[108]
MOAC	✓	×	×	×	✓	✓	×	×	[109]
HXL	✓	×	✓	×	×	×	×	×	[110]
FOAF	×	✓	✓	×	×	×	×	×	[96]
CROnto	✓	×	×	×	✓	✓	×	×	[111]

1.2.3.9 Discussion

During our literature review, we studied several ontologies and meta-models developed in the context of disaster response. However, these ontologies and meta-models are restricted to one ERO, to a specific case or a specific purpose [112]. They define knowledge about organizations, resources, processes, or disasters, but not all of these. Furthermore, none of the mentioned works cover the operational vocabularies of the different ERs in detail in a way that the ontology could be used to ensure semantic interoperability between the different stakeholders. According to the FEI, these ontologies focus only on data and services while process and business are two major concerns that should be considered when addressing interoperability requirements. Once they are taken into account, they represent the orchestration of stakeholders' actions. This motivates us to develop a shared vocabulary between the operational ERs (firefighters, healthcare services, public order forces, and public authorities) in order to enhance collaboration and communication during multi-agencies disaster response. Therefore, to develop the ontology, we consider the four interoperability concerns: data (different semantics, in different formats and stored in different databases of ERs) is employed by services (different functions and roles of each stakeholder) and services are used by process (coordination of ERs' processes of intervention) to perform business (multi-organization response to a disaster). In this work, we aim to define disasters and their different types, when and where they occurred, the involved stakeholders; their roles and chain of command, victims, resources, and so on.

1.3 Orientations

Following the Paris and Nice multiple mass causality terrorist attacks, and the devastation of Xynthia storm, French ERs highlighted the need to focus on improving the disaster response process. Within this context, the French project POLARISC for "Plateforme OpérationnelLe d'Actualisation du Renseignement Interservices pour la Sécurité Civile" is started in 2017 in order to consider the different challenges that ERs face during operational disaster response. This three-year project is funded by the European regional operational program FEDER/FSE « Midi-Pyrénées et Garonne 2014-2020 » as part of the call for projects "Easynov2016".

To overcome the aforementioned shortfall, POLARISC is a semantically driven operational command system based on the French emergency response doctrine. The aim is to concentrate on the operational level of disaster response and to address the identified challenges it faces through a software that is designed to provide reliable and timely information to those involved in the operational management of large-scale disasters. In particular, the focus is on:

1. Offering to all ERs a real-time operational picture of the situation in order to enable multi-level coordination.
2. Guarantying an appropriate and intelligible visualization of the ongoing operations on the disaster site by taking into consideration the graphical charter of each ERO.

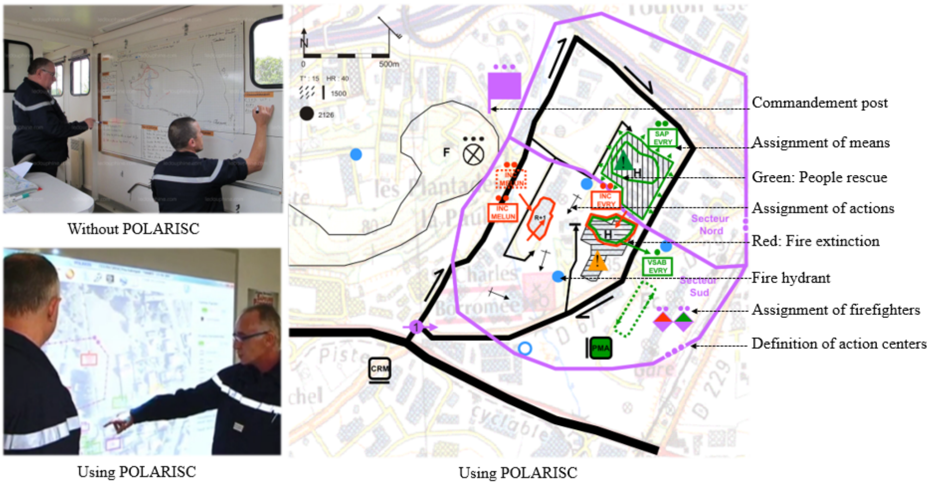

Figure 1.17: Common operational picture of the disaster site.

3. Formalizing the knowledge of the ERs to ensure an effective understanding of the exchanged information.

4. Consolidating information and ensuring semantically interoperable communication and effective flow of information across all ERs involved in the process of disaster response.

5. Improving the victims' evacuation process by enabling interoperability of data between the disaster area and the healthcare institutions.

6. Enhancing the resource allocation process and real-time tracking of resources.

In terms of interoperability, POLARISC proposes a federated and integrated approach to resolve conceptual, technological, and organizational barriers concerning data, service, process, and business.

POLARISC is addressed to all ERs including firefighters, police, gendarmerie, healthcare units, and public authorities to enable coordination during the multi-agency response. POLARISC end-user platform will be used by the unified command center, the different command and control centers, the command post of each ERO, and stakeholders on the disaster site. POLARISC system will not substitute the ERs systems but it will be used as an extension. It will replace the use of whiteboards to represent the disaster situation and resource allocation on the field. Figure 1.17 depicts a comparison between the firefighters' command post using whiteboards when responding to a disaster and then using the POLARISC platform. One can notice that real-time exchanges will take less time than usual and will increase the response efficiency and effectiveness.

POLARISC is a software solution that plays the role of mediation among ERs. It is composed of three layers; user interfaces layer, mediation layer, and POLARISC core layer. Figure 1.18 illustrates the architecture of the POLARISC platform as a whole system.

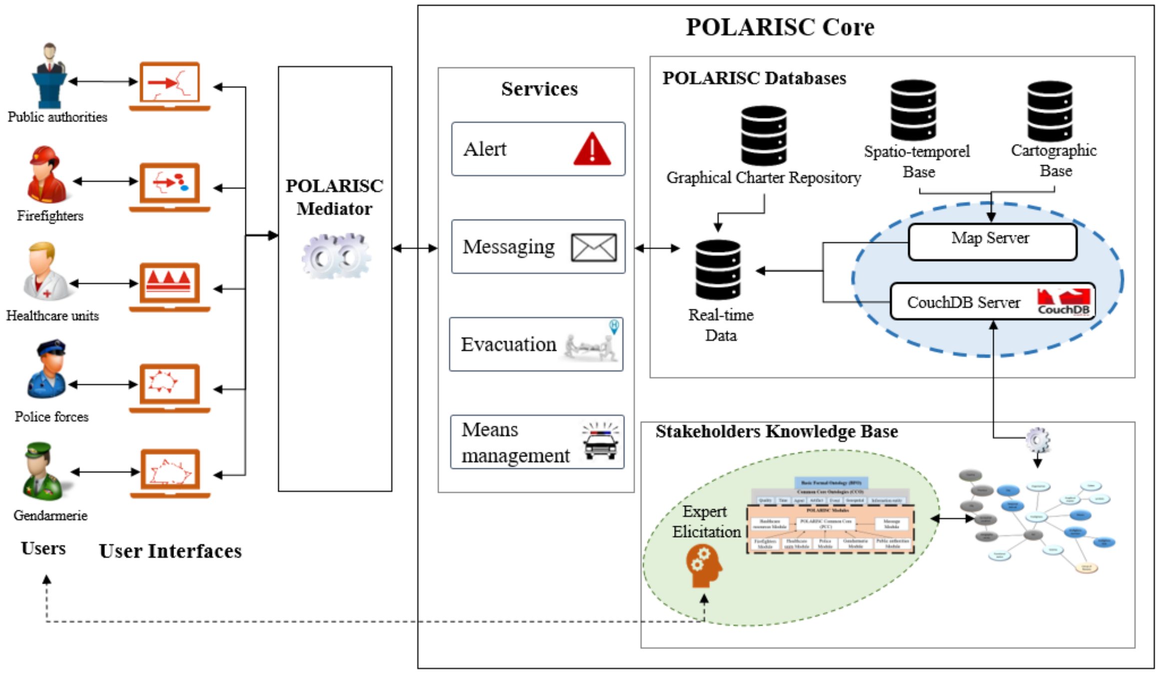

Figure 1.18: POLARISC general architecture.

First, concerning the users' interface layer, POLARISC aims to offer a real-time operational picture of what is happening on the disaster site by considering the different graphical symbols and colors' codes of each stakeholder. It is built based on the French national graphical charter of ERs. Using the proposed platform, each stakeholder can place units, action centers, and resources on the map to represent the situation on the site according to the topology of the field, the weather, the direction and strength of the wind. In order to achieve it, an icon repository is deployed. The operational picture is generated by the geospatial resources data. These latter are composed of data about geographic location represented primarily by images and tables or grids of observed or calculated attributes. These resources are used in our system for purposes of cartographic mapping to enable the visualization of the common operational picture of the disaster site.

Second, the POLARISC mediator is responsible for guaranteeing an appropriate understanding of the situation by the different ERs. It plays the role of gateway between end-user and the core system so as to provide a suitable representation of the requested information according to stakeholder's characteristics (for instance, their vocabularies, the graphical symbols that signate them, the color codes assigned to them.). Accordingly, all information exchange is organized and distributed to all involved ERs by POLARISC mediator. The aim is that ERs will be able to understand external information and all parties share the same extent of such derived information.

Third, the core system is composed of a knowledge base, a set of integrated services and geospatial resources bases. The map server and the knowledge base server generate real-time data that will be used as input in the services component.

Accordingly, a knowledge base composed of a suite of ontologies is proposed. Ontology, together with a set of instances of its classes constitutes a knowledge base. It is the main source of information, capable of being exploited by all the stakeholders. Such a shared vocabulary will resolve terminological inconsistencies and establish semantic interoperability among ERs. It formalizes the complex knowledge of the French ERs. Moreover, it will represent all the key kinds of processes associated with disaster response and all levels (strategic, tactical and operational) and it defines the technical vocabulary of all the involved stakeholders (e.g. means, roles, action centers, processes). That is, it covers a variety of interoperability concerns arising for example because data are collected in different formats, because the different functions of different stakeholders are not taken into account, and because there are failures of coordination among different groups of emergency responders.

To query and infer new knowledge from the ontology, the semantic query language SPARQL is employed. To use the ontology, POLARISCO is serialized in both OWL and JSON-LD and stored in CouchDB [113]. This transformation is accomplished using Protégé. CouchDB is an open-source NoSQL database. It is also a document-oriented database that can be requested by HTTP. Our adoption of it is driven by the fact that CouchDB enables the application to be used offline. The real-time common operational picture of the disaster site and information exchanged among ERs is based on the internet connection, which is unreliable. Therefore, thanks to CouchDB, all the features of POLARISC platform can be used offline to store data and to make it available once the system is back online.

POLARISC is intended to enable a set of integrated services, that will be used on demand by POLARISC mediator, designed to support the ERs when responding to disasters.

1. The victims' evacuation service aims to facilitate the process of taking care of victims by finding as quickly as possible the appropriate healthcare institutions and reserving it according to the patient state.
2. The alert service is connected to the ERs' systems and aims to improve ways stakeholders respond to disasters by delivering immediate emergency alerts and warnings to the stakeholders. It also supports other ERs not far from the disaster site in preparing to send backup if it is needed.
3. The means management service will facilitate the process of assigning resources to the disaster site by checking its availability.
4. The messaging service attempt to ensure semantically enhanced information exchange and mutual understanding among the involved ERs. Each stakeholder will receive information according to his own vocabulary and with his own semantics.

This thesis is part of the project POLARISC. In fact, the project is the outcome of a collaboration between the National School of Engineering of Tarbes (ENIT) and the enterprise EXYZT (σ: the set of, X, Y, Z: spatial landmark (3D), T: temporal dimension). Specifically, the focus of this work in on the knowledge base, the messaging service, and the evacuation service. EXYZT is in charge of the rest of the system's components.

1.4 Conclusion

In this chapter, we introduced some background and basics, discussed the related works, and presented the main orientations. First, we presented the disaster management process followed by a detailed analysis of the response phase concerning levels of war, actors, the workflow of stakeholders' processes, and information flow. Second, we discussed the different challenges that should be considered for a successful multi-stakeholders disaster response. Then, we identified interoperability as a key feature to enable communication and coordination between stakeholders. Accordingly, we studied the different crisis information management system in terms of interoperability and disaster response challenges. Afterward, we presented ontologies and more specifically upper-level ontologies. Next, we presented a review of the existing ontologies for the disaster response field. The outcomes of the state of the art acted as the stepping stones for the proposal of the project POLARISC. The main contributions of this work will be presented in the next chapters.

Chapter 2

A Modular Ontology: POLARISCO

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2.1 Introduction

The heterogeneity of terminologies and technical vocabularies of the various involved ERs may lead to a misunderstanding and subsequently a lack of coordination and collaboration among stakeholders. Maintaining a semantically interoperable information exchanged among these latter is a major challenge. However, to date, there is still a lack of computable format of stakeholders' operational vocabularies to be used to semantically transform the information to be exchanged from one stakeholder to another. To overcome these issues, in this work, we aim to formalize and semantically capture the complex knowledge of the different French EROs (firefighters, healthcare units, police, gendarmerie, and healthcare services) in order to provide a common, shared vocabulary that will be exploited latter to facilitate information exchange among ERs. Accordingly, we elaborate a suite of domain ontologies. In this chapter, the different steps of the development process of POLARISCO are presented.

2.2 The selection of an ontology building methodology

When developing a large ontology, the development process becomes more critical. The choice of an appropriate ontology building methodology is crucial. Accordingly, we adopted

METHONTOLOGY [89] as a development methodology. It is well structured, the most mature approach [114], and one of the most comprehensive methodologies [88] to build an ontology. Moreover, METHONTOLOGY is very helpful when developing large ontologies [92].

METHONTOLOGY splits their activities into two levels: the development activities include specification, conceptualization, formalization, integration, implementation and maintenance, and the support activities include knowledge acquisition, evaluation, and documentation.

More specifically, the ontology development activities start with the specification phase. It defines the purpose of the ontology (including its objectives, scenarios of use, end-users), its domain and scope, and defining the Competency Questions (CQs) following the objectives set. CQs consist of a set of questions that the ontology must be able to answer [93]. It includes also knowledge acquisition and elucidation from books, conducting interviews with experts, and even from other existing ontologies. Second, the conceptualization phase concerns organizing and structuring the acquired knowledge in a complete Glossary of Terms (GT) and the construction of a taxonomy of classes. Taxonomy is often referred to as the backbone of an ontology built using the relation "is-a". Third, in the formalization phase, the conceptual model is transformed into a formal model by establishing semantic relations among classes. Then, the implementation phase requires the use of an ontology development environment to implement the ontology. Afterward, the evaluation phase is to carry out a technical judgment of the ontologies [89]. It involves the verification and validation steps. The verification guarantees the correctness of the ontology. The validation assures that the ontology corresponds to the intended results. The final phase is maintenance.

In fact, we have adjusted METHONTOLOGY phases according to our needs as shown in Figure 2.1. More specifically, because of the fact that ontology development is necessarily an iterative process [88], we added a review and revision step to enable the iterative development of the ontologies and their continuous refinement.

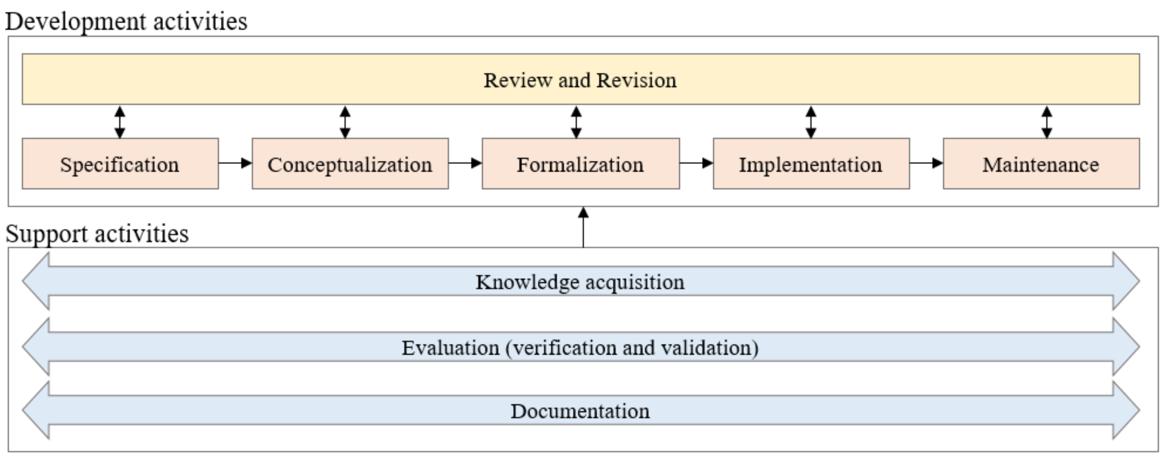


Figure 2.1: The different components of METHONTOLOGY.

2.3 POLARISCO development process

The so-called POLARISCO (POLARISC Ontology) aims to semantically capture the knowledge of the ERs involved in the disaster response process. In this section, we present in details the different steps of the development process (specification, conceptualization, formalization, implementation) of POLARISCO. The knowledge acquisition activity is exploited during the specification phase. The integration is done during the implementation phase. Then, the evaluation and validation step is presented.

2.3.1 Specification phase

This section puts forward more details about the proposed ontology in terms of objectives, requirements, competency questions and knowledge acquisition.

2.3.1.1 POLARISCO objectives

POLARISCO is a domain ontology built with the main goal of making the best possible definition of stakeholders' technical vocabularies and make them understandable, accessible, and computer analyzable. It is developed for establishing a commonly shared conceptualization that defines classes and their relationships that will be exploited latter to promote semantic interoperability among the different stakeholders. More accurately, POLARISCO defines knowledge about stakeholders' data, service, process, and business in the different levels of disaster response by focusing more on the operational level.

2.3.1.2 POLARISCO requirements

Because the diversity of ERs' vocabularies was bound, naturally, to complicate the design of the ontology, we adopted the principles of modularization to build our ontology. The notion of modularization comes from software engineering, it provides a strategy for structuring and organizing ontologies. The benefits of ontologies modularization have been recognized by the semantic web community. The main benefits of such a method, are manipulating smaller ontologies, reducing the complexity of ontologies development, and reusing each module independently. An ontology module may be defined as "a reusable component of a larger or more complex ontology, which is self-contained but bears a definite relationship to other ontology module" [115]. An arithmetic metaphor is also summarized in:

$$module = a\ (smaller)\ ontology + intermodules\ links. \tag{2.1}$$

We consider the different goals of ontology modularization including scalability for querying data and reasoning on ontologies, scalability for evolution and maintenance, complexity management, understandability, context-awareness and personalization, and reuse [115].

The idea is to develop separate ontological modules so that they can stand alone. In fact, there are two contexts of ontology modularization. The first context is ontology integration and interrelation. It concerns the construction of a large ontology basing on the combination of self-contained, independent and reusable modules [116]. That is to say, various ontology modules are putted together to compose a new ontology. The second context is module extraction and module partition. It deals with decomposing an ontology onto smaller and more manageable modules. In this work, our focus is on modules integration and interrelation.

To develop consistent, relevant, and useful ontological modules, we considered a set of general principles [11], [10]. Arp et al [11] pointed out that "a good ontology will be one that is designed in such a way as to respect these principles". One of these best practice is the use of a domain-neutral upper-level ontology. A domain ontology is called well-founded if it is based on a foundational ontology. This principle states that it is advantageous if the ontologies that will be shared among multiple actors share a common upper layer of well-defined classes [77]. Any class of the ontology should be defined in a consistent manner according to an upper-level ontology. The use of upper-level ontologies provides a common ontological foundation for domain ontologies [117]. It allows more effective quality assurance of ontology development. In this work, the use of upper-level ontologies is fundamental to promote semantic interoperability among the different proposed ontological modules by enabling their integration. Moreover, it facilitates the reuse of our ontology by others. Another adopted principle is reusing classes from existing mid-level and domain ontologies.

Accordingly, the key requirements of POLARISCO are listed as follows:

- The ontology represents the domain of disaster response.
- The ontology applies the principle of modularization.
- The ontology is aligned with a top-level ontology.
- The ontology reuses classes from mid-level and domain ontologies.

2.3.1.3 Competency questions

The CQs consist of a set of questions stated in natural language, targeting the main elements of the ontology, that this latter must be able to answer [93]. They should cover all needed information mentioned in the domain knowledge that the ontology should cover. To do so, we start by exploring the domain knowledge by referring to the domain experts (see Figure 2.2). In particular, POLARISCO considers:

- Different kinds of disasters, the needed resources, and the corresponding acts.
- Disasters are events that occur in specific spatial-temporal regions. Hence, POLARISCO also represents the times and places where disasters occur.

- That each ER has its own process of intervention, means, roles, chain of command, and so on.

- That each type of ER has its own unique vocabulary, including: firefighters, police, gendarmerie, healthcare units, and public authorities.

- That each stakeholder has a controlled vocabulary for victim states.

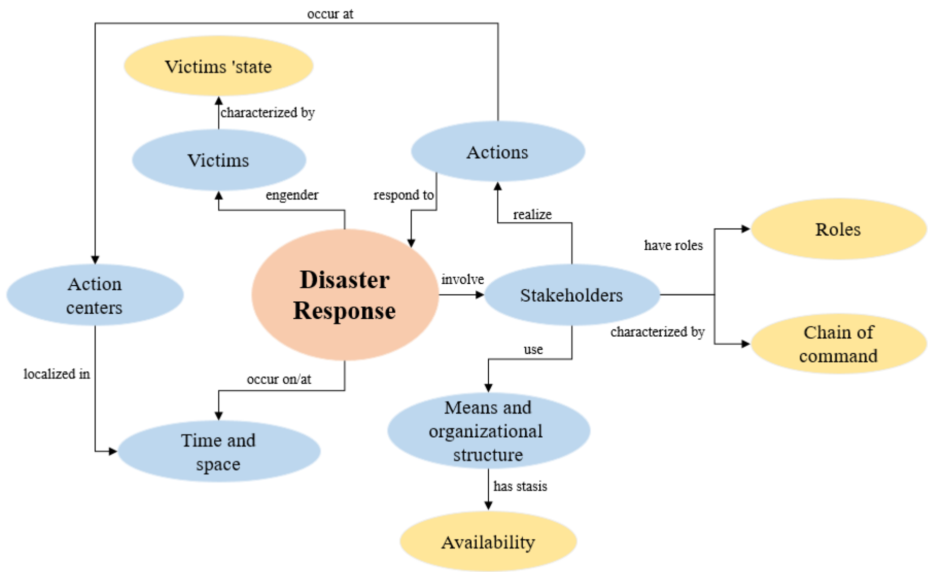


Figure 2.2: POLARISCO's domain knowledge.

Basing on POLARISCO domain knowledge, we defined the CQs in coordination with the domain experts (firefighters, healthcare units, police, etc.). Any scenario that will be used as means of validation of the proposed ontology should be able to answer the defined CQs. In the following, some examples of the defined CQs are presented in Table 2.1.

2.3.1.4 Knowledge acquisition

To discover, elicit, and extract knowledge about the field of disaster response, we conducted interviews with stakeholders of each EROs (including firefighters, healthcare units, police, gendarmerie, and public authorities) and we studied their technical resources and feedback documents to get specific and detailed knowledge about classes, their properties, and their relationships. In addition, after reviewing the different ontologies proposed in the field of disaster management as presented in chapter 1, we identified some classes that can be reused from existing ontologies such as DO, ERO, and PS/EM ontology.

Table 2.1: Examples of Competency Questions (CQs).

CQ_i	CQ
1	What is the nature of the disaster?
2	When did the disaster <X> take place?
3	Where did the disaster <X> take place?
4	What is the criticality level of the disaster <X>?
5	Which ER was involved in the operation <X>?
6	Where was the advanced medical post of the healthcare units located?
7	Who was the operational commander of the operation <X>?
8	Who was the public authority that commanded the operation <X>?
9	What were the acts of the operation <X> of the ER [Y]?
10	Who is competent to search and rescue the drowned Person?
11	How many people were affected by the disaster <X>?
12	What was the state of the victim <X>?
13	What means were used in the operation <X>?
14	What types of means are needed to respond to the disaster <X>?
15	What are the available means?
16	How many beds are available in the hospital [X]?
17	Where was located the action center <X> of the ER <Y>?
18	Who sent and who received the message <X>?
19	What is the type of the message[X]?
20	What are the needed resources for the disease [X]?

2.3.2 Conceptualization phase

In this phase, the domain knowledge is organized in a GT and then structured in a taxonomy. In fact, it consists of defining a hierarchy of classes linked by subclass or "is-a" relations by starting with a single top-most class connected to all other classes through unique branches [11]. In fact, the hierarchy of terms is defined following the philosophy of the widely used upper-level ontology Basic Formal Ontology (BFO). In what follows, we present the upper-level ontology, mid-level ontologies, and then the proposed modules that represent the domain of disaster response.

2.3.2.1 Basic Formal Ontology (BFO)

An upper-level ontology is used as a foundation that provides a representation of that portion of reality that is common across all domains. Our justification for choosing BFO is twofold: we looked for a realist upper ontology that represents the world as it is, — we might say that the ontology encapsulates the knowledge of the world that is associated with the general terms used by scientists in the corresponding domain [11]. More accurately, BFO is a realist, formal and domain-neutral upper-level ontology; it is designed to represent at a very high level of generality the types of entities that exist in the world and the relations that hold among them. It is utilized as a starting point for the categorization of entities and relationships by over 300 domain ontologies, especially in the biomedical, military, and intelligence domains. It has already recently become an ISO standard (ISO 21838-2).

As a starting point, BFO uses the class entity as a common representation of anything that exists, including objects, processes, and qualities; then there are two main divisions of the class entity "continuants" and "occurrents" in a single framework as a top-level distinction between entities. "Continuants" are entities that endure through time. "Occurrents" are entities that happen or develop in time, such as processes. Figure 2.3 and Table 2.2 illustrate the structure of BFO using some of its main classes and their characterizations.

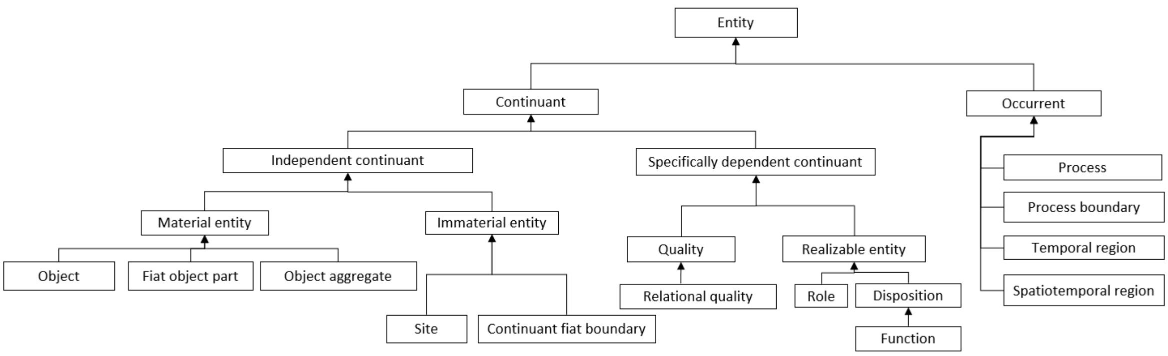


Figure 2.3: A fragment of the BFO's classes hierarchy.

Table 2.2: BFO classes and their characterizations.

Class	Characterizations
"entity"	Anything that exists or has existed or will exist.
"continuant"	An entity that continues or persists through time while maintaining their identity and have no temporal parts. It is a dependent or independent object.
"occurrent"	An entity that occurs happens or develops in time: events or processes or happenings.
"independent continuant"	A continuant entity that is the bearer of some qualities, it can maintain their identity and existence through gain and loss of parts, dispositions or roles, and changes in their qualities.
"generically dependent continuant"	An entity that is dependent on one or more other independent continuants. This latter can serve as its bearer. It is similar to complex continuant patterns of the sort created by authors or through the process of evolution.
"specifically dependent continuant"	An entity that depends on one or more specific independent continuants for its existence. It exhibits existential dependence and has two subcategories: quality and realizable entity.
"process"	An occurrent entity that exists in time by occurring or happening has temporal parts and always depends on at least one material entity. It can be partitioned into temporal parts in different ways and at different levels of granularity.
"quality"	A specifically dependent continuant that depends or inheres in an entity at all and is fully exhibited or manifested or realized in that entity.
"disposition"	A realizable entity whose bearer is some material entity.
"role"	A realizable entity which exists because the bearer is in some special physical, social, or institutional set of circumstances in which the bearer does not have to be, and is not such that, if it ceases to exist, then the physical make-up of the bearer is thereby changed.

2.3.2.2 The Common Core Ontologies (CCO)

As a mid-level ontology, the Common Core Ontologies (CCO) [118] meets most of our requirements since it defines a modular set of extensible classes and relations that can be connected to our domain ontology. It descends from BFO and consists of ten modular ontologies as illustrated in Figure 2.4:

- Information Entity Ontology represents generic types of information and their relationships.
- Agent Ontology defines individual agents (Persons) and coordinated groups of individuals (Organizations) as well as their roles.
- Quality Ontology represents the attributes of agents, artifacts, and events.
- Event Ontology represents processes in which agents are participants.
- Artifact Ontology provides the designed qualities and functions of material entities.
- Time Ontology defines temporal intervals and the relations that hold among them.
- Geospatial Ontology defines the basic vocabulary for describing the locations of agents and occurrences of events including spatial regions.
- Units of Measure Ontology represents standard units of measurement.
- Currency Unit Ontology represents standard monetary currency.
- Extended Relation Ontology defines approximately seventy-five relations that link together the content of the Common Core Ontologies.

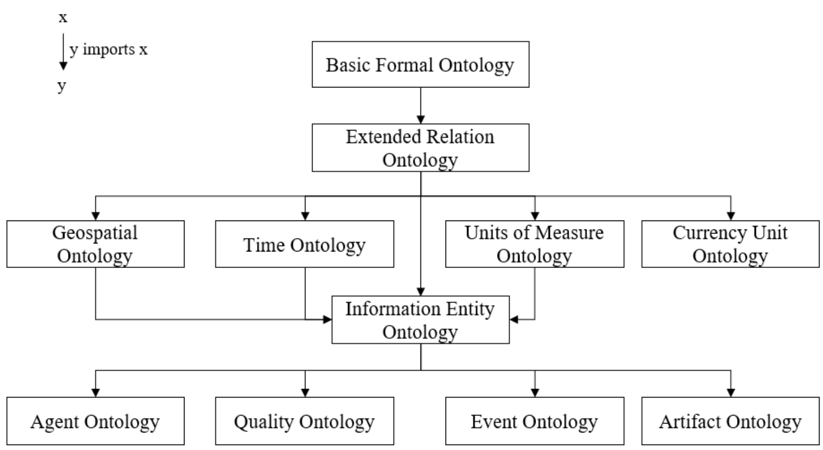


Figure 2.4: CCO modules hierarchy.

A simplified explanation of the diverse modules is presented in [118]: "In CCO, agents (People and Organizations), use artifacts to perform actions that occur in both time and space, and are differentiated from other agents and artifacts via attributes". The development of CCO started in 2010 in IARPA [1] Knowledge, Discovery and Dissemination programs. The purpose of these core ontologies is to provide a structured base vocabulary that serves as a unified semantics. Once extended, it represents the content of any data sources.

2.3.2.3 POLARISCO modules

First, a module is defined for each stakeholder. Thus, we proposed five modules to represent the knowledge of the different involved ERs namely firefighters module, healthcare units module, police module, gendarmerie module, and public authorities module. After that, we built a Glossary of Terms (GT) for each module by referring to the knowledge elucidated during the acquisition step. Terms include classes, properties, instances, and relations. We found that there are several terms in common among the stakeholders' modules, which led us to define a core module named PCC (POLARISC Common Core). It includes the general classes that all stakeholders share (e.g. disasters, transmission means, victims) in order to ensure more semantic interoperability among the modules and to facilitate their integration. Afterward, we defined a message module that formalizes acts of communication between stakeholders, and a healthcare resources module that defines victims' diseases and the associated staffing and equipment. To summarize, to aid ERs in overcoming the problem of semantic heterogeneity, POLARISCO is an extension of BFO and CCO [2] that integrates eight modules. Figure 2.5 illustrates the proposed modules and their import structure. These modules include:

- Polarisc Common Core module
- Firefighters module
- Healthcare units module
- Police module
- Gendarmerie module
- Public authorities module
- Messages module
- Healthcare resources module

2.3.3 Formalization phase

After defining the modules and the related GT, in this phase, the proposed taxonomy is transformed into a formal model by establishing relations among classes to ensure a complete

[1] https://www.iarpa.gov/
[2] except units of measure ontology and currency unit ontology

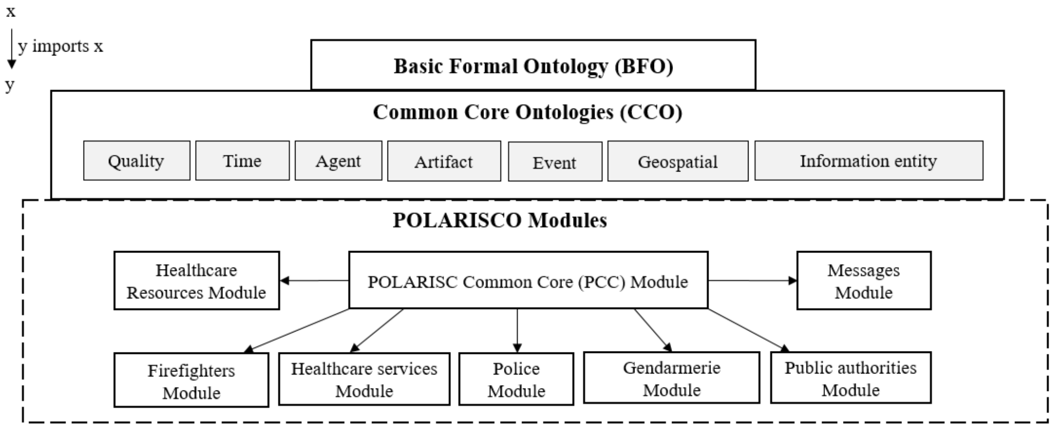


Figure 2.5: The different modules of POLARISCO.

taxonomical hierarchy for the ontology. To connect the different classes, we use a hybrid approach, based on a top-down alignment to BFO and CCO, and a bottom-up alignment to define classes that are gathered during the knowledge acquisition step. We approach in two ways by generalizing high-level classes to lower levels and by abstracting the low-level data to the higher-level class.

In virtue of extending BFO and CCO to define POLARISCO modules, we reused generic relations imported from other external ontologies. In particular, CCO reuses the Relations Ontology (RO) [77] which is a collection of OWL2 [3] relations intended to be shared among various ontologies. Another ontology called RO-Bridge has been developed by adding domains and ranges constraints to the relations defined in RO to be used to relate BFO classes. The RO-Bridge relations that are reused in POLARISCO are presented in Table 2.3. Furthermore, we identified the need to define other relations specific to POLARISCO to relate the classes of the different modules (Table 2.4).

2.3.3.1 POLARISC Common Core (PCC) module

In the following, the various classes and their relationships of PCC module are presented. We started by defining what is a disaster. According to the US Department of Homeland Security National Response Framework, a disaster is defined as any event, natural or manmade, that results in extraordinary levels of mass casualties, damage, or disruption severely affecting the population, infrastructure, environment, economy, national morale, and/or government functions [13]. Hence, a disaster is an event characterized by an instantaneous boundary such as temporal intervals (a beginning and an ending). While BFO defines the occurrent entities as a kind of process that exists in time by occurring, happening or developing in time. Thus, we defined a “disaster” as a subcategory of the class “bfo: process”.

Next, we classified “natural disaster” and “human-made disaster” as subclasses of “dis-

[3] https://www.w3.org/TR/owl-ref/

Table 2.3: The reused RO-Bridge relations.

Relation	**Domain**	**Range**
has_role	Independent continuant	Role
agent_in	Person or Organization	Process
has_input	Process	Continuant
has_quality	Independent continuant	Quality
supervises	Person or organization	Person or organization
has_participant	Process	Continuant
located_in	Material entity	Spatial region or site
occurs_on	Process	Temporal region
is_part_of	Independent continuant	Independent continuant
realized by	Realizable entity	Process
occurs_at	Process	Spatial region or site
has_starting_instant	Temporal region	Temporal region
caused_by	Process	Process
has_function	Independent continuant	Function
has_sender	Act	Agent
has_recipient	Act	Agent
sends	Agent	Act
is_designated_by	Entity	Designative Information Content Entity

Table 2.4: POLARISCO relations.

Relation	Domain	Range
respond_to	Agent	Process
installed_by	Site	Agent
take_place_in	Process	Environmental feature
has_day	Temporal region	Temporal region
has_month	Temporal region	Temporal region
has_year	Temporal region	Temporal region

aster" as shown in Figure 2.6. We defined kinds of natural disasters and classified them under climatological, geophysical, meteorological, and hydrological categories. Under each category, we defined subclasses such as "earthquake disaster", "tsunamis disaster", "tornado disaster", "cyclone disaster". Then, we defined kinds of human-made disasters and classified them under "accident disaster", "explosion disaster", "terrorist attack disaster" and "fire disaster" categories. Furthermore, we defined five types of "accident disaster" including "transport accident disaster", "domestic accident disaster", "radiologic accident disaster", "chemical accident disaster" and "nuclear accident disaster". A "transport accident disaster" can be either "air crash disaster", "road accident disaster", "railway accident disaster" or "maritime accident disaster". Note that a disaster is amenable to cause another disaster. For this purpose, we defined the relationship "caused_by" to show the connection that exists among the different disasters. For instance, an "explosion disaster" is caused by a "chemical accident disaster".

To know when and where a disaster occurred, spatial and temporal contexts should be considered. To do so, we defined the following three relationships (see Figure 2.7); First, "occurs_at" relates a disaster to "cco: geopolitical entity" (e.g. city, country, town, village). Second, "take_place_in" relates a disaster to "cco: environmental feature". In fact, CCO defines an environmental feature as "a material entity that is a natural or man-made feature of the environment". Third, "occurs_on" relates a disaster to a "date". We reused time ontology of CCO that provides the basic vocabulary for describing when events occur. Thus, we defined the "date" as a subclass of "bfo: one-dimensional temporal region" and a date has a "cco: day", a "cco: month" and a "cco: year".

Various ERs from different EROs are engaged in the process of disaster management. We reused agent ontology from CCO to define the different stakeholders. It represents agents, their qualities, and the roles they have. The notion of Agent comprises both an individual agent as a person and a coordinated group of individuals as an Organization. A "cco: organization member" is affiliated with some "cco: organization" and has a role some "cco: organization Member Role". Every instance of "cco: organization member" is equivalent to an instance of "cco: person" that has role some instance of "cco: organization member role".

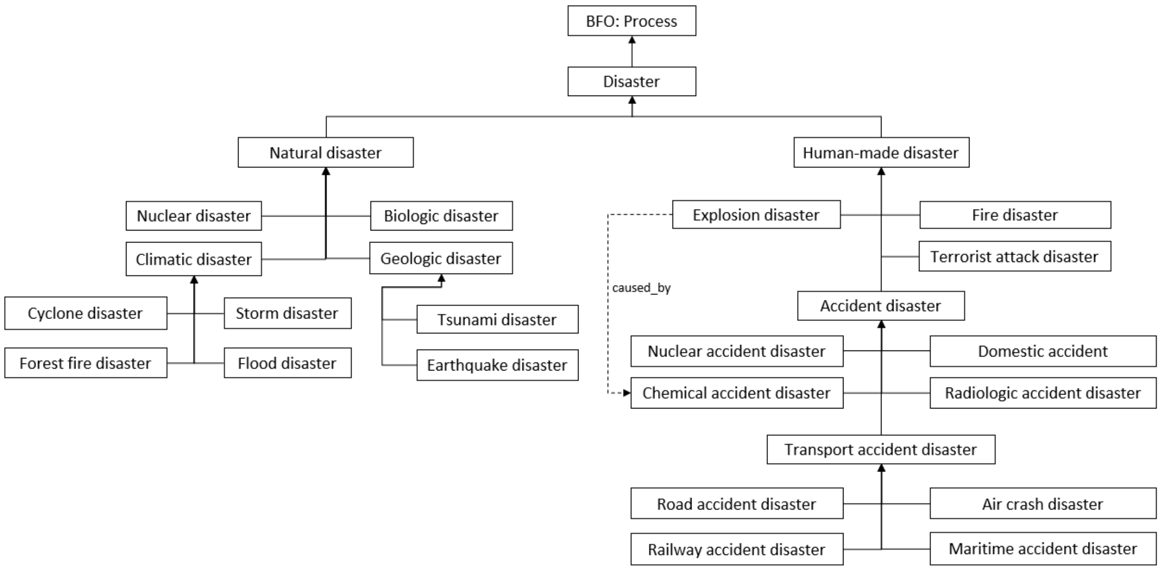


Figure 2.6: Disasters classification in POLARISCO.

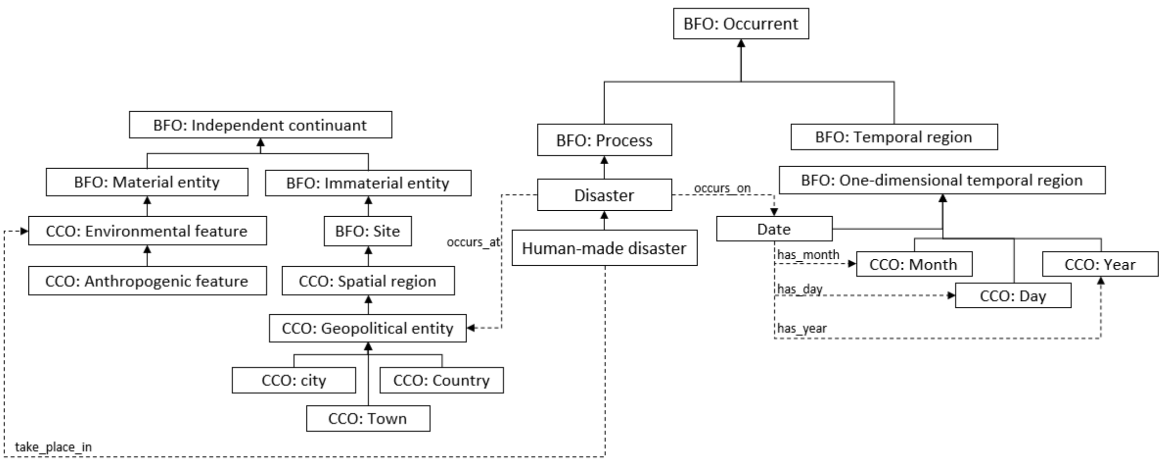


Figure 2.7: Spatial and temporal regions of a disaster.

The latter usage can be defined first-order logic (FOL) as follows:

$$\forall x, y \; [Organization\_member(x) \; \equiv \; (Person(x) \; \wedge \; y(Organization\_member\_role(y) \wedge x \; has\_role \; y))] \tag{2.2}$$

Afterward, stakeholders perform acts to respond to a certain disaster. We reused "cco: act" from the event ontology of CCO. In fact, stakeholders carry out whether real intervention or a training program as an act of response to a certain disaster. Thus, we defined "simulated act" and "real rescue act" as subclasses of "response act". The response act is performed by stakeholders. Therefore, we relate "cco: organization member" to "response act" using the relation "agent_in". Furthermore, acts are performed in a specific localization. We reused the geospatial ontology of CCO and we defined an "action center" as a subclass of "cco: spatial region".

Aside from stakeholders and their acts, there are material entities involved in the process of disaster response. BFO defines a "material entity" as an "independent continuant". Three types of material entities are recognized by BFO [11]: "object", "object aggregate", and "fiat object part". CCO inserted the artifact module as "object". We defined the resources involved in the operational disaster response under "artifact". It includes "infrastructure", "equipment" and "mean". As a common resource among the ERs, we defined "transmission mean" as a subclass of "mean" which can be "radio" or "telephone". We defined also "hospital" as an infrastructure that contains beds. We defined "bed" as a subclass of "equipment". Furthermore, we defined the "digital radio network" used by the involved stakeholders as a subclass of "infrastructure". Figure 2.8 illustrates a partial view of the PCC module.

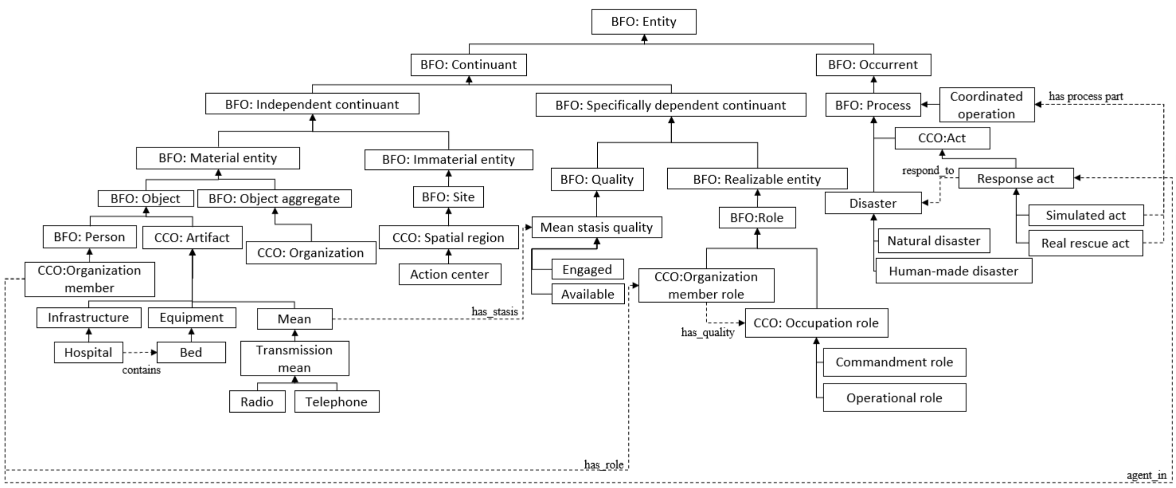


Figure 2.8: POLARISC Common Core (PCC) module.

Moreover, an organization member or an ordinary person could be injured, or killed as a result of a disaster. Hence, a person can be a victim. BFO defines a role as a realizable entity that is possessed by its bearer because of some external circumstances and it is always optional. Therefore, we classified "victim role" as a subclass of the realizable entity "bfo: role" (see Figure 2.9). A "victim" is a defined class such that a victim is a person, has a victim role, and is characterized by a specific stasis. We defined "victim stasis" under "cco: stasis" which is defined as a "process". Thus, we relate "victim" to "victim stasis" using the relation "has_stasis". For each ER, "victims' stasis" is designated by specific codes or acronyms. For this purpose, we defined "victim stasis code identifier" as a subclass of "cco: code identifier". A "code identifier" is defined by CCO as "a non-name identifier that consists of a string of characters that was created and assigned according to an encoding system such that metadata can be derived from the identifier". A victim can be defined in FOL as follows:

$$\begin{aligned} \forall x, y, z[Victim(x) \; \equiv \; (Person(x) \; \wedge \; y(Victim_r ole(y) \; \wedge \; x \; has_r ole \; y) \; \wedge \\ z(victim \; stasis \; code \; identifier(z) \; \wedge \; x \; has_s tasis \; z))] \end{aligned} \tag{2.3}$$

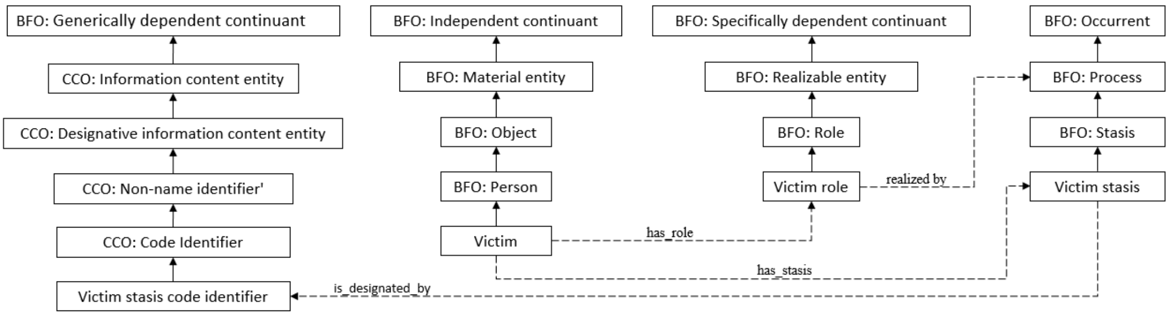


Figure 2.9: Definition of victims in PCC module.

2.3.3.2 Stakeholders modules

Concerning the stakeholders' modules, we used the PCC module as a starting point, and then we added the appropriate classes related to each module. For each stakeholder module (firefighters, healthcare units, police forces, gendarmerie, and public authorities), we defined the following classes. We defined stakeholders' roles. For instance, in the firefighters module, we added an equivalent class to "firefighters' member" that is equivalent to a "bfo: person" and has a role "firefighters' role" (see Figure 2.10).

Next, each organization member has either a command role or an operational role. For this purpose, we defined "command role" and "operational role" as subclass of "cco: occupation role". In fact, CCO define "occupation role" as a role that an agent is expected to fulfill. For example, in the police module, we modeled the "general director of the police forces" as a "command member" and the "police officer" as an "operational member". Furthermore, we used the relation "supervised_by" to put forward the hierarchical levels of command among the different roles; the "police officer" is supervised by the "general director of the police forces"

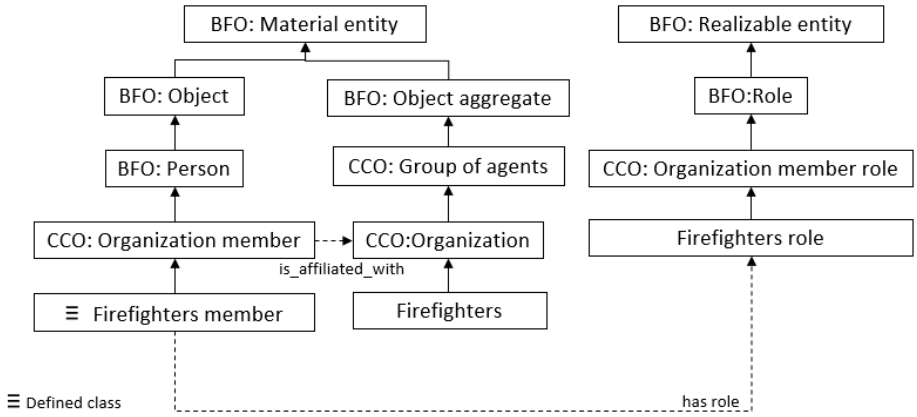


Figure 2.10: Definition of firefighters' roles.

(see Figure 2.11).

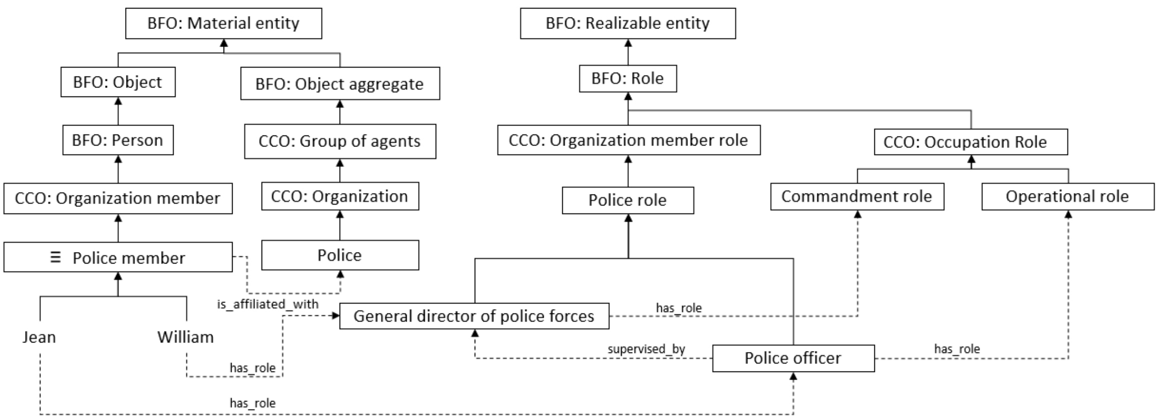


Figure 2.11: Definition of police forces' roles.

Afterward, we defined specific acts of each stakeholder under "cco: act". For example, we defined "act of gathering", "act of rescue", and "act of evacuation" as healthcare units acts. Each act is realized by a specific actor and necessitates a particular mean. Accordingly, we define relations among acts, means and roles in order to figure out what is needed for a specific act so as to respond to a certain disaster (Who does what? And using what?) (see Figure 2.12).

In addition, for each mean, we defined its function and its stasis (whether it is "active" or "planned"). For instance, the "act of rescue" involves minimum one "doctor". Moreover, the act of evacuation needs "ambulance" and/or "helicopter" to transport the victims and subsequently an "ambulance" needs an "ambulance driver". Thus, we defined "healthcare units mean" under two categories "vehicle" and "mean of air transport" as subclasses of "pcc: mean". In addition, the "act of gathering" is realized by a "gathering officer".

Once the victims are gathered and then sorted, either they receive first-aid according to their stasis or they will be transferred to the appropriate hospital. In fact, victims receive instant medical care in a "medical advanced post", known by its French initials PMA, installed by the "gathering officer" and managed by a "doctor". The PMA is installed in a safe zone near the disaster location in case of mass casualty management. We define "medical advanced post" as a subclass of "zone", which is a "bfo: site". Furthermore, "medical advanced post" is equivalent to "functional zone" and is located in "bfo: site". The latter usage can be defined as follows:

$$\forall x, y, z[Medical\ advanced\ post(x) \equiv (Functional\ zone(x) \wedge y(Site(y) \wedge x\ located_in\ y) \wedge z(Rescue(z) \wedge z\ needs\ x))] \tag{2.4}$$

Concerning the designation of the victim's stasis, it is different from one actor to another. For this purpose, we added for each stakeholder the appropriate class that describes the victim stasis as subclasses of "pcc: victim stasis".

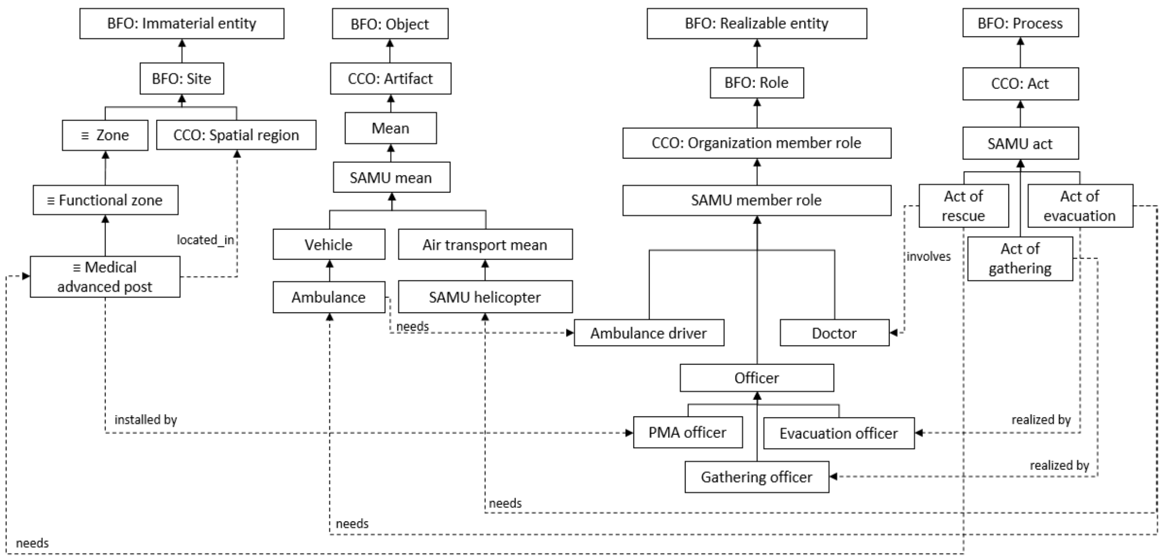


Figure 2.12: Acts, roles, and means in the healthcare units module.

Indeed, one of the principles to respect in building a useful ontology is that any class of the ontology should be defined in a consistent manner [11]. Thus, we created annotations for each class (including a definition, the spelling out of abbreviations, and labels). The recommended best practice for creating definitions of classes is to use the Aristotelian form. This latter can be used for the formulation of definitions regardless the ontological domain [11]. It concerns defining a class using its subclass; the formulation of a class definition depends in a first step on the "is_a" hierarchy as shown in Figure 2.13.

Once stakeholders modules are formalized, we defined relations that exist among these

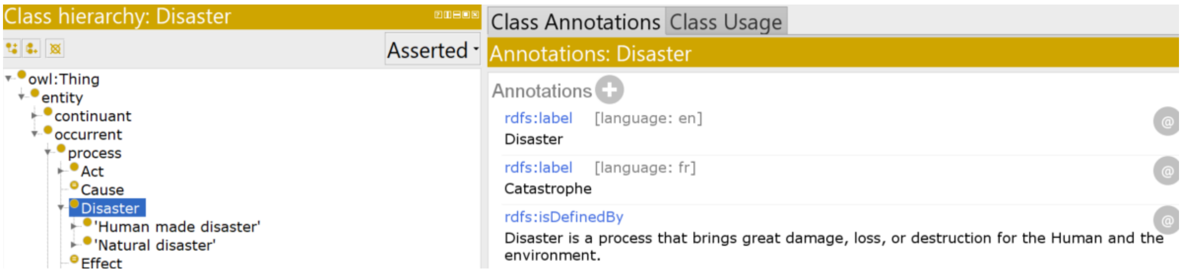


Figure 2.13: Example of annotations (definition and label).

latter. Each module has at least one relationship with other modules. Figure 2.14 shows a partial view of the stakeholders' modules. For example, the public authorities module is linked to the rest of the stakeholders modules with the relationship "supervises". Accordingly, the "interior minister" supervises the command member of each ERO.

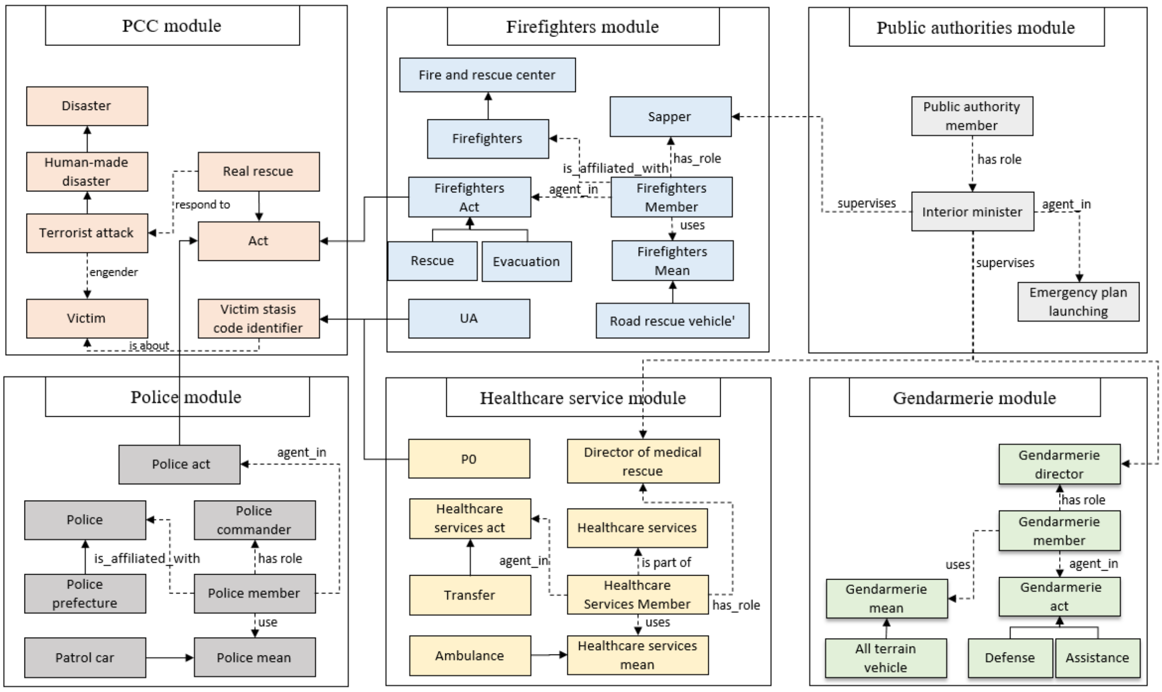


Figure 2.14: Partial view of stakeholders' modules.

2.3.3.3 Messages module and healthcare resources module

The message module and the healthcare resources module are defined on the basis of the PCC module and are related to the stakeholders modules. In addition, the message module reuses classes from PS/EM ontology. The healthcare resource module imports disease ontology (DO) and reuses classes from eagle-i resource ontology (ERO). The first module concerns classes related to the process of information exchange among stakeholders (e.g. message, message's type). The second module defines victims' pathologies and the needed healthcare resources including materials and staff that should be available in hospitals. Further details will be presented respectively in chapter three and four.

2.3.4 Implementation phase

The proposed formalization models are encoded in the ontology implementation language OWL and implemented using Protégé [4]. Protégé is the most widely used ontology editor [119]. It was initially developed by the Stanford University Center for Biomedical Informatics Research for more than two decades. It is an open source software system that enables ontology engineers to create and edit ontologies. It provides a set of mechanism to define entities, relationships, properties, and instances. Moreover, it enables knowledge visualization and reasoning

To implement the proposed ontology, we, first, imported BFO and CCO to build the PCC and message modules by using the "owl: import" feature of OWL2. Second, we imported PCC to construct the stakeholders' modules. Then the different modules are merged together and integrated into one ontology POLARISCO. Table 2.5 presents the classes and relations of the global ontology.

Table 2.5: Classes and relations of POLARISCO.

Ontology	Number of Classes	Number of Relations
Developed ontology		
POLARISCO	641	25
Imported ontologies		
BFO	27	-
CCO	199	240
Classes from existing ontologies		
Imported ontologies		
PS/EM ontology	15	-
DO	54	-
ERO	93	-
Total	1029	265

2.3.5 Evaluation phase

In this subsection, we present POLARISCO evaluation through the verification step followed by the validation step.

[4] https://protege.stanford.edu/

2.3.5.1 POLARISCO verification

Ontology verification consists of ensuring that the ontology is built correctly. It answers the question "are we producing the ontology right?" [120]. The aim is to make sure that the constructed ontology is consistent, its classes are satisfiable, and the inferred model reflects the intended semantics desired by the ontologist. To do so, we checked the consistency of POLARISCO modules following a three steps process.

Firstly, we used the reasoner HermiT, which is an OWL2 reasoner integrated into Protégé, to determine the consistency of POLARISCO. We identified a set of contradictory relations that we resolved and we made sure that the ontology doesn't have any more logical incoherencies.

Second, to check if the ontology responds to the fixed specifications, we translate the CQs into SPARQL (Simple Protocol and RDF Query Language) language so as to query the ontology. Figure 2.15 and Figure 2.16 show some examples of the obtained results.

- CQ1: "What types of means are needed to respond to a forest fire?"

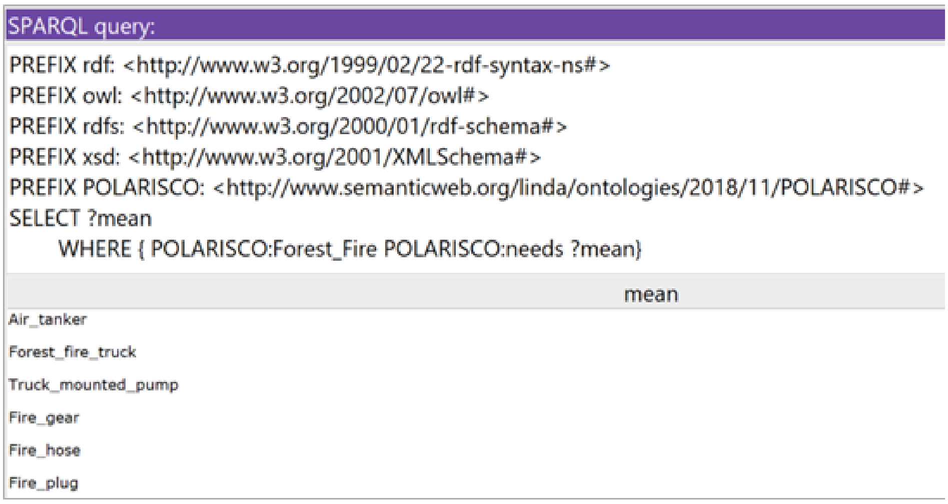
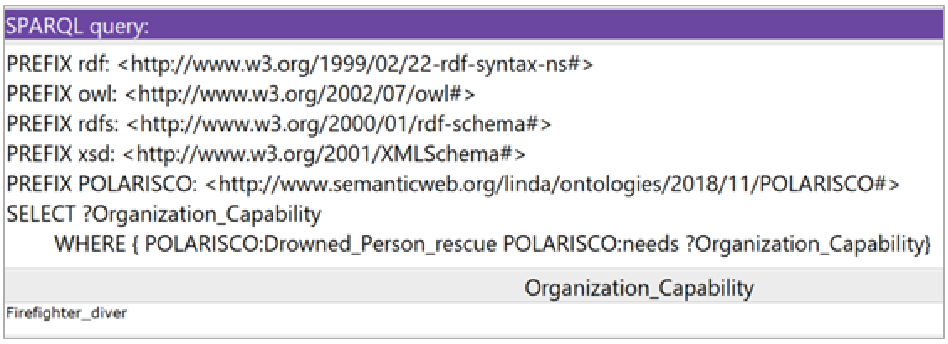


Figure 2.15: SPARQL query and results of the CQ1.

- CQ2: "Who is competent to search and rescue the drowned Person?"

Third, the proposed ontological modules are evaluated according to specific metrics. In the literature, several works have examined modularity metrics [121]. The aim is to provide a quantitative perspective of the quality of the ontology and its covered knowledge. In the following, we present the different identified evaluation metrics, their definitions, and the equations to measure them [122]. In fact, there are four categories of metrics; structural metrics, logical metrics, relational metrics, and richness metrics.



```
SPARQL query:
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX POLARISCO: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>
SELECT ?Organization_Capability
    WHERE { POLARISCO:Drowned_Person_rescue POLARISCO:needs ?Organization_Capability}
```

Organization_Capability
Firefighter_diver

Figure 2.16: SPARQL query and results of the CQ2.

- The structural metrics depend on the structural and hierarchical properties of the module. It concerns counting components of the module (e.g. classes, axioms). Calculating the structural metrics involves calculating the size, the relative size, the atomic size, and the cohesion.

  - The size represents the number of entities in a module |M|. It is the sum of the number of classes |C|, object properties |OP|, data properties |DP|, and individuals |I|.

$$|M| = |C| + |OP| + |DP| + |I| \tag{2.5}$$

  - The relative size refers to the size of the module compared to the global ontology O. It is calculated as follow:

$$Relative\ size(M) = \frac{|M|}{|O|} \tag{2.6}$$

  - The atomic size is the average size of interdependent axioms in a module. In fact, the term atom represents a group of axioms, that have dependencies between each other, within an ontology.

$$Atomic\ size(M) = \sum_{i}^{n} \frac{Atom_i}{|M|} \tag{2.7}$$

  - The cohesion represents the extent to which entities in a module are related. It is measured using the following equation:

$$Cohesion(M) = \begin{cases} \sum\sum \frac{SR}{|M|(|M|-1)} & if |M| \succ 1 \\ 1 \quad otherwise \end{cases} \tag{2.8}$$

- The logical metrics involve correctness metrics and completeness metrics.

  - The correctness means that every axiom that exists in a module also exists in the global ontology O.

$$Correctness(M) = True\ if\ M \subseteq O \tag{2.9}$$

– The completeness implies that the meaning of every entity in a module is maintained in the global ontology O. It is checked as follows:

$$Completeness(M) = True \ \ if \sum_{i}^{n} Axioms(Entity_i(M)) \models Axioms(Entity_i(O)) \quad (2.10)$$

- The relational metrics represent the relations and behaviors that modules exhibit with other modules. Among these relational metrics, inter-module distance (IMD) represents the number of modules that have to be considered to relate two entities where NM is the number of modules to consider and $|(M_i, M_n)|(|(M_i, M_n)| - 1)$ represents the number of possible relations between entities in a set of modules.

$$IMD(M) = \begin{cases} \sum_{E_i, E_j \in (M_i, M_n)} \frac{NM(E_i, E_j)}{|(M_i, M_n)|(|(M_i, M_n)|-1)} & if |(M_i, M_n)| \succ 1 \\ 1 \quad otherwise \end{cases} \quad (2.11)$$

- The richness metrics are used to measure the quality of an ontology using attribute richness and inheritance richness.

  – The attribute richness (AR) refers to the average number of attributes per class where att is the number of attributes of all entities.

$$AR(M) = \frac{|att|}{|C|} \quad (2.12)$$

  – The inheritance richness (IR) expresses how the knowledge is distributed in a module. It constitutes the number of subclasses per class where H is the number of subclasses.

$$IR(M) \frac{\sum_{i}^{n} |H|}{|C|} \quad (2.13)$$

To investigate the evaluation of POLARISCO modules, we used the Tool for Ontology Modularity Metrics (TOMM) software. Specifically, it allows users to upload an ontological module together with the global ontology and to calculate the different metrics of the module. The results are shown in Table 2.6. The relative size values of the different modules, which are less than 1, indicate that the modules are relatively smaller comparing to the global ontology POLARISCO. The atomic size of POLARISCO modules designates that there is an average between 2.65 and 3.78 axioms grouped together. The cohesion of a module indicates how closely related its entities are to each other. We can conclude that the PCC module has the lowest

Table 2.6: POLARISCO metrics.

Modules	$N_{classes}$	$N_{properties}$	Structural metrics				Logical metrics		Relational metrics	Richness metrics	
			Size	RS	AS	Cohesion	Correctness	Completeness	IMD	AR	IR
M_{PCC}	46	8	61	0.047	3.56	0.01	true	true	82780	0.001	0.782
$M_{Firefighters}$	147	2	202	0.158	3.31	0.13	true	true	5983	0.872	0.993
$M_{Healthcareunits}$	132	3	192	0.151	3.78	0.14	true	true	4526	0.751	0.946
M_{Police}	96	2	148	0.116	3.09	0.11	true	true	3986	0.623	0.895
$M_{Gendarmerie}$	77	1	141	0.110	2.94	0.11	true	true	3189	0.658	0.986
$M_{Publicauthortities}$	38	1	70	0.054	2.65	0.02	true	true	1260	0.125	1.121
$M_{Messages}$	47	6	56	0.043	3.52	0.07	true	true	853	0.391	0.994
$M_{Healthcareresources}$	58	2	229	0.179	3.49	0.09	true	true	589	0.009	1.586

cohesion value and stakeholders modules have the highest cohesion value due to the strong relatedness of its different classes such as acts, roles, and means. Most of POLARISCO modules do not contain a lot of attributes, as the AR is less than 1 for all the modules. The inheritance richness is between 0.782 and 1.586 which indicates that the different modules are horizontal ontologies because of the high number of direct subclasses. Concerning the IMD, the PCC module has the highest value because all the rest of the modules import it. Then, stakeholders modules have a high IMD value due to the defined inter-module relations such as equivalent classes that will be shown in the next chapter. Furthermore, the logical metrics indicate that the ontology correctness and completeness are true. These analyzed results prove the consistency of the different proposed modules and the global ontology POLARISCO.

2.3.5.2 POLARISCO validation

To validate an ontology, it should be tested by comparing the meaning of the ontology definition against the intended model of the world [120]. It enables to answer the question "Are we producing the right ontology?". Accordingly, to validate the proposed ontology and to show its usability, on the one hand, POLARISCO is tested by means of a concrete real-world use-case as will be presented in the following. On the other hand, POLARISCO is exploited by the messaging service in the next chapter to present its ability to promote semantic interoperability among stakeholders and how a communication act can be improved across different ERs.

We identified the November 13, 2015 terrorist attacks in Paris as a good scenario since it provides several interoperability challenges that should be resolved. The data used in this use-case comes from ERs reports and feedback.

In fact, this multi-site terrorist attack was the first of this magnitude in France [4]. It refers to six coordinated attacks that were carried out by three groups of gunmen. At least 130 deaths have been confirmed and 413 were injured and taken care of in Paris Region hospitals. The first attack took place at the concert hall "Le Bataclan", four attackers entered the building and started shooting randomly with automatic weapons. Hundreds of people were held hostage in a theatre. At the same time, three explosions occurred just outside the "Stade de France", a stadium in "Saint-Denis" just outside Paris; during an international football match. Other locations were hit, four bars and restaurants were successively targeted by attackers armed with automatic weapons.

To respond to these multiple terrorist attacks, the prime minister started by launching the emergency plan by alerting the needed ERs to intervene in time. There were mainly four commanders of the operational acts of the different stakeholders on the field; Director of Operations (DO), Commander of Rescue Operations (COS), Director of the Medical Response (DSM), and Commander of Police Operations (COP). For each site, there were one COS and one DSM.

Many operating forces were involved and a lot of means were mobilized to respond to these attacks [7]. Table 2.7 outlines stakeholders' mobilization and resource allocation to respond to the terrorist attacks of November 13, 2015, in Paris.

Table 2.7: Resources allocation ans stakeholders mobilization during the response to the Paris attacks.

Stakeholders' mobilization and resources allocation	Number
Fire units	450 firefighters deployed on sites, 250 firefighters in support, and 1000 firefighters in stand by.
Reinforcements by Civilian Firefighters	260 including sixty deployed for evacuations only
Healthcare units	Forty medical teams on sites
Police forces	3000 police officers
Means	125 firefighters' vehicles deployed Twenty-one Intensive Care Ambulances
Hospitals	Activation of the "White Plan" in seventeen hospitals of assistance ("Assistance Publique - Hôpitaux de Paris") and activation of two Military Hospitals (HIA Percy and Begin)
Casualties Grouping Point (PRV)	Seven PRV

All the presented data about the November 13, 2015 terrorist attacks in Paris were translated into ontology instances to test the usability of POLARISCO. To do so, we used the SPARQL Query editor that is integrated into Protégé. Examples of the made queries include:

1. When and where occurred the terrorist attacks?
2. Who were the command members of each involved unit?
3. What were the used means of firefighters and healthcare units in the Paris terrorist attacks?
4. How many vehicles and operational firefighters were engaged in the Paris terrorist attacks?
5. What were the act of the stakeholders to respond to the Paris terrorist attacks?

Query 1: When and where occurred the terrorist attacks?

As shown in Figure 2.17, the temporal and the spatial region of the occurred multi-site terrorist attacks are identified. Concretely, we extracted the date of the attacks, the constructed features where the attacks took place (theatre, stadium, bars, restaurants), and their geopolitical location (city or town).

Query 2: Who were the command members of each involved unit?

When responding to a disaster, it is fundamental to distinguish the exact role of each involved stakeholder. Accordingly, as can be seen in Figure 2.18, the command members that were responsible for managing the operational acts on the field are extracted with their specific roles and affiliation. The result of this query illustrates how we can navigate in the stakeholders' modules.

Query 3: What were the types of means used by the firefighters and healthcare units to respond to the Paris terrorist attacks?

There are various types of means used either by firefighters or healthcare units to evacuate the victims in case of a disaster. The type of employed mean depends mainly on the victims' stasis. As demonstrated in Figure 2.19, we extracted the utilized means by firefighters and healthcare units. Firefighters used vehicles of succor and assistance to victims (VSAV). Concerning the healthcare units, they used helicopters to transfer victims in an absolute emergency to the appropriate hospital in a minimum of time, and Intensive Care Ambulances (ICA) for victims in a relative emergency.

Query 4: How many vehicles and operational firefighters were engaged in the Paris terrorist attacks?

As showing in Figure 2.20, we extracted the number of firefighters deployed on sites and, the number of firefighters' vehicles engaged in the action center of people succor.

Query 5: What were the acts of the involved stakeholders to respond to the Paris terrorist attacks?

Each ERO on the disaster scene has a specific act to perform. As showing in Figure 2.21, we extracted the different acts done during the response to the Paris terrorist attacks and the ERO that realized each act respectively.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX RO: <http://www.obofoundry.org/ro/ro.owl#>
PREFIX ERO: <http://www.ontologylibrary.mil/CommonCore/Upper/ExtendedRelationOntology#>
PREFIX POLARISCO: <http://www.semanticweb.org/linda/ontologies/2019/3/POLARISCO#>
SELECT  ?Date  ?Constructed_Feature ?Geospatial_Region
     WHERE {POLARISCO:Paris_Terrorist_attacks ERO:occurs_on ?Date.
                POLARISCO:Paris_Terrorist_attacks POLARISCO:take_place_in ?Constructed_Feature.
                  ?Constructed_Feature RO:located_in ?Geospatial_Region}
```

Date	Constructed_Feature	Geospatial_Region
13/11/2015	Bataclon	Paris
13/11/2015	Le_Comptoire_Voltaire_Restaurant	Paris
13/11/2015	Le_Corillon_Bar	Paris
13/11/2015	Belle_Equipe_Bar	Paris
13/11/2015	Petit_Cambodge_Restaurant	Paris
13/11/2015	Stade_de_France	Saint-Denis

Figure 2.17: SPARQL query and results of spatial and temporal information of the terrorist attacks.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX RO: <http://www.obofoundry.org/ro/ro.owla#>
PREFIX AO: <http://www.ontologyrepository.com/CommonCore/Mid/AgentOntology#>
PREFIX ERO: <http://www.ontologyrepository.com/CommonCore/Upper/ExtendedRelationOntology#>
PREFIX POLARISCO: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>

SELECT DISTINCT ?organization_member ?commandement_role ?organization
     WHERE { ?organization_member AO:supervises POLARISCO:Paris_Terrorist_attacks.
               ?organization_member ERO:has_role ?commandement_role.
               ?organization_member AO:is_affiliated_with ?organization
```

organization_member	commandement_role	organization
Jean_Pierre_Tourtier	Director_of_the_Medical_Response	Healthcare_units
Daniel_Landrieu	Commander_of_Police_Operations	Police
Philippe_Boutinaud	Commander_of_Rescue_operations	Firefighters
Jean-François_Carenco	Director_of_operations	Public_authority

Figure 2.18: SPARQL query and results of the involved stakeholders and their corresponding commanders.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX AO: <http://www.ontologyrepository.com/CommonCore/Mid/AgentOntology#>
PREFIX POLARISCO: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>
Select ?organization ?mean
Where { POLARISCO:Paris_Terrorist_attacks  AO:uses   ?mean.
          ?mean   AO:is_used_by   ?organization
}
```

organization	mean
Firefighters	VSAV
Healthcare_units	ICA
Healthcare_units	Heli-SMUR

Figure 2.19: SPARQL query and results of the means used by firefighters and healthcare units.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ero: <http://www.ontologyrepository.com/CommonCore/Upper/ExtendedRelationOntology#>
PREFIX polarisco: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>
SELECT  (count(?organization_member) as ?MemberCount) (count(?vehicle) as ?VehicleCount)
      WHERE {  ?vehicle polarisco:used_in polarisco:CA_PS_75.
                  polarisco:CA_PS_75 polarisco:engage ?organization_member
               }
```

MemberCount	VehicleCount
57	35

Figure 2.20: SPARQL query and results of the engaged vehicles and stakeholders.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ero: <http://www.ontologyrepository.com/CommonCore/Upper/ExtendedRelationOntology#>
PREFIX polarisco: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>
SELECT  ?act ?organization
      WHERE {  polarisco:Paris_Terrorist_attacks  ero:has_process_part  ?act .
                   ?act  ero:realized_by  ?organization  }
```

act	organization
Act_of_public_order	Police_forces
Act_of_recognition	Police_forces
Act_of_hostage_release	Police_forces
Act_of_fire_extinction	Firefighters
Act_of_gathering	Firefighters
Act_of_gathering	Healthcare_units
Act_of_rescue	Healthcare_units
Act_of_rescue	Firefighters
Act_of_triage	Healthcare_unit
Act_of_victims_extraction	Firefighter
Act_of_evacuation	Firefighters
Act_of_evacuation	Healthcare_units
Act_of_threat_neutralization	Police_forces

Figure 2.21: SPARQL query and results of stakeholders performed acts.

2.3.6 Discussion

In this chapter, we presented a description of the development process of POLARISCO. The proposed process is complete, starting from stakeholders' requirements and specification to the implementation and the evaluation of the ontology by means of a concrete case study. We adopted METHONTOLOGY due to its transparent logical structure, maturity, and clarity comparing to other methods. But, it does not enable the iterative development of the ontology. Therefore, we adjust it according to our needs by adding a review and revision step to facilitate the iterative development of our proposed ontological modules. Figure 2.22 shows the sequences of steps leading to the formation of the proposed ontology.

We started by identifying the ontology purpose, requirements and CQs. It was important to be clear from the beginning why the ontology was built and what its intended uses were. Then, the most important terms of the operational disaster response were determined. The specification step was performed basing on domain experts' knowledge. Afterward, in the conceptualization step, at first, we defined the different modules to be developed and we structured the knowledge by proposing a GT for each module (classes, properties, instances, and relations). The definition of the different GT made us realize that there are a lot of terms in common among stakeholders' modules which led us to define the PCC module. Once the modules are defined and to facilitate their integration and to enable semantic interoperability among them, the use of BFO and CCO was crucial. In the formalization step, the conceptual model was transformed into a formal model by defining the different relationships.

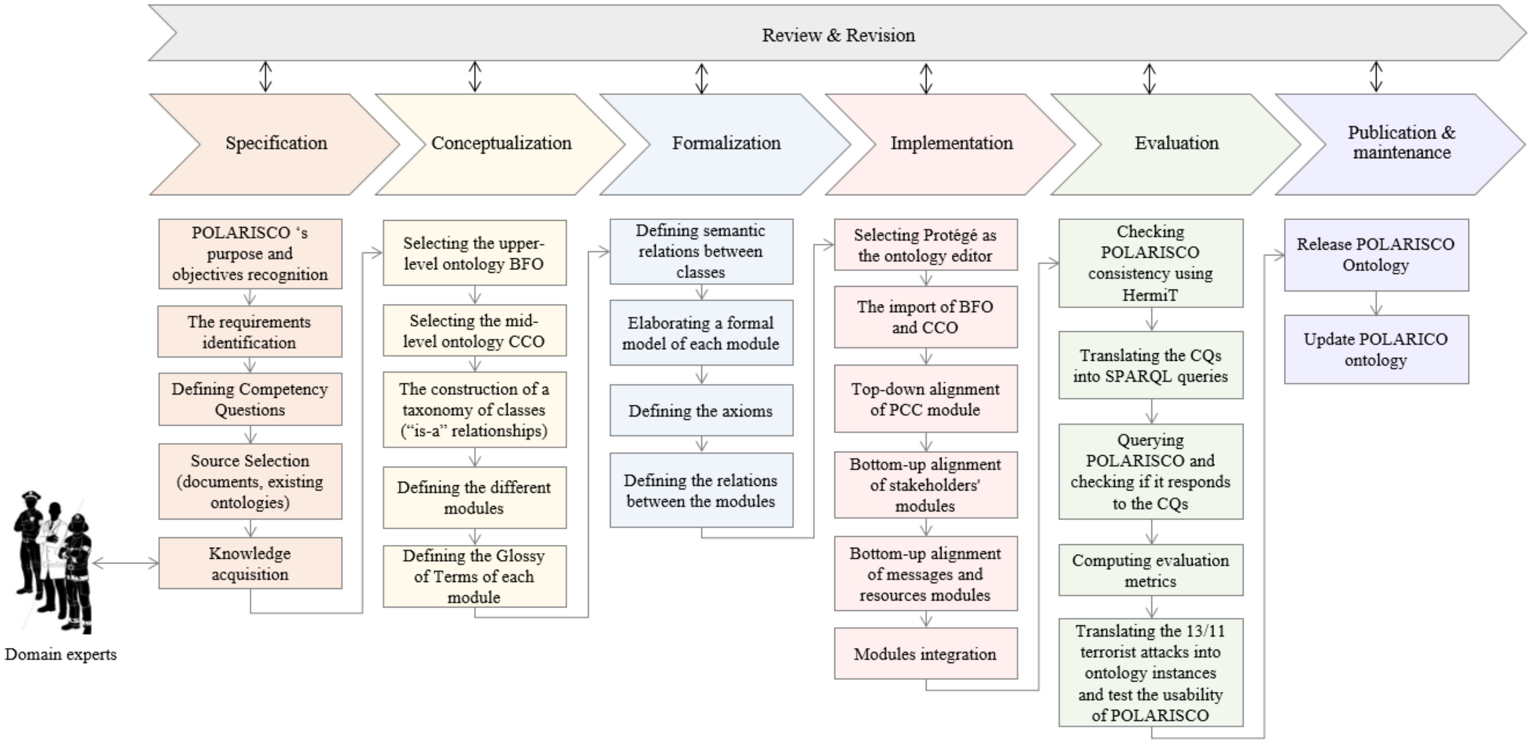


Figure 2.22: The sequences of steps of POLARISCO development process.

In the implementation step, the different modules were implemented in OWL and integrated to come up with POLARISCO. Concerning the evaluation and validation step, POLARISCO was queried to check if it responds to the defined CQs and if it is consistent enough. The Paris terrorist attacks use case was a good example to put forward the utility and the consistency of the proposed ontology. Finally, POLARISCO [5] is available on-line and it will be updated by considering the changes that can occur in the disaster response domain to ensure its reliability.

POLARISCO respects all the fixed requirements. First, it shares a common upper layer of well-defined classes by reusing BFO and CCO. The use of upper-level ontologies facilitates the reuse of POLARISCO classes in other ontologies. Second, the advantage of adopting the principle of modularization to build the ontology is twofold; on the one hand, it reduces the complexity of ontologies development by manipulating smaller ontologies, on the other hand, it enables its reuse as separate and independent modules. Third, POLARISCO captures the operational vocabulary including data, service, process, and business of each stakeholder. it covers also the strategic and tactical levels by defining the commandment members and their respective roles. In fact, one of the unique aspects of this work is that the process of development of the ontology has been involving emergency experts from the specification to the validation. Indeed, the development of POLARISCO was difficult and very delicate especially that the proposed ontology will be used as the core of the messaging service and will influence the precision and the pertinence of the information exchange process.

2.4 Conclusion

In this chapter, we presented POLARISCO, a modular suite of ontologies, that reuses BFO as upper-level ontology and CCO as a mid-level ontology to define the knowledge of French stakeholders including firefighters, healthcare units, police, gendarmerie, and public authorities. One strong point of the adopted ontological approach is that POLARISCO is tested by means of real data and validated by stakeholders and emergency experts. POLARISCO can be used in English or in French. Every class of the ontology is defined in a consistent manner. In chapter 3, POALRISCO will be exploited by means of a messaging service that will enable the semantic translation of the exchanged information and ensure that all parties will share the same extent of such derived information. Accordingly, the second phase POLARISCO validation focuses on providing evidence about the semantic interoperability improvement among ERs.

[5] https://github.com/LindaElmhadhbi/POLARISCO

Chapter 3

PROMES: An Ontology-driven messaging service

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3.1 Introduction

Because they reflect different areas of expertise, EROs use differing terminologies, which are difficult to reconcile. These issues lead to ambiguities, misunderstandings, and inefficient exchange of data and information among those involved, which can impede the response process and slow decision making. We, therefore, hypothesize that formalizing communication and promoting semantic interoperability might improve information exchange among stakeholders and thereby allow a more coherent response to the disaster. In this chapter, we propose an ontology-based messaging service as part of POLARISC platform and on the basis of the Emergency Data Exchange Language (EDXL) standards. The parties involved will continue to use the terminologies to which they are accustomed, but the system will resolve inconsistencies and thereby enhance mutual understanding by enabling a semantic translation among ERs. In the following, we present the proposed approach and the evaluation of its robustness and efficiency.

3.2 State of the art

3.2.1 Improving communication between emergency responders

Interoperability in a heterogeneous environment is primordial so as to enable communication and collaboration among different ERs where diverse technologies are used that are often incompatible such as UHF/VHF radios, 800 MHz radios, push-to-talk, etc. The fact that frequency bands are different from one stakeholder to another may cause a loss of time to dispatch manually the radio communication. Therefore, the use of radio as the ANTARES [1] network to connect individual actors in France – with each ERO using its own frequency – contributes both to the lack of cross-ERO interoperability and to the difficulty of inter-organizational communication [6]. Inter-organizational communication is difficult in most scenarios; stakeholders are unable to exchange information with peers. Even though, ERs use the same type of radio communication, they may not know the channel used by their peers [123].

Scholz, et al. [124] conducted interviews with firefighters about their overall experiences and described how can communication failure impact the response process. An incident commander points out: “This is something that we openly admit. Wireless communication problems happen to firefighters, and they happen a lot. If the crew is well organized or badly organized, the communication equipment dies and leaves us high and dry, or partially gives out. Sometimes it breaks down, or there is interference, or the battery dies, someone keeps on squawking with the talk button, there are countless things which can go wrong”.

As a direct result of the mentioned point, choosing the best communication system to enable information exchange between ERs is crucial. Text messaging was shown to be more reliable than voice [123]. Hence, POLARISC system proposes a web-based text messaging service. In case of internet failure, the use of CouchDB ensures the availability of data once the system is back on-line.

In the literature, information exchange across ERs have posed a long-standing challenge. Bhattacharjee [125] proposes an Android mobile phone disaster messenger application that enables sharing of situational information in the absence of a network infrastructure. However, this solution is oriented around use by volunteers for purpose of disseminating post-disaster information.

Authors in [126] propose an integrated mobile information and communication system called MIKoBOS (Mobile Information and Communication System for Public Safety Organizations) which enables data communication among stakeholders during emergency response operations by integrating the operations of different types of mobile terminals, communication technologies, and advanced satellite communication.

Another approach for ensuring data exchange is presented in [26]. This concerns an information system designed to deliver data by using a client-server architecture and an ad

[1] $http://cpi.bage.free.fr/photo/32/presentation_antares.pdf$

hoc routing protocol. In reality, this system has low reliability when deployed.

Jiang et al. [127] provide a hierarchical cloud-fog platform that enables real-time human communication and geolocation services through the integration of a standardized incident command system (ICS) and different smart devices including wireless mesh network elements, heads-up displays, and virtual beacons. The platform allows the orchestration of real-time video feeds of the incident, the real-time tracking of medical supplies, patients, and responders' locations, and the visualization of situational awareness.

Moghaddam et al. [128] propose a cluster-based hierarchical topology for multi-hop Device-to-Device (D2D) communication and cognitive radio to enable stakeholders' communication without infrastructure support. However, the proposed approach is not yet implemented and tested.

The studied projects are intended to improve communication among ERs by proposing only technological solutions. To the best of our knowledge, there is no approach that considers the semantics of the exchanged data despite its huge importance in communication. In fact, the semantic heterogeneity of data leads to very serious issues when these data need to be exchanged. One word may be interpreted differently from one context to another. Take the word "tank" for instance. As shown in Figure 3.1, in an armored vehicle context, the term refers to a certain kind of specialized armored vehicle, but in a firefighter context, it refers to a type of container used for holding water. When information needs to be exchanged between stakeholders working in these two contexts, it is not evident how the expression "we need a tank immediately" should be interpreted [129].

If the information systems used in these contexts stand to each other in a relation of semantic interoperability, then this would mean that the information exchanged has a common meaning for both the requester and the provider of the requested services and data [33]. The information system will, under the hood, as it were – most users will not be aware of its operations – semantically translate the word 'tank' into some unambiguous expression (water container, armored vehicle) in such a way as to ensure share meanings. Accordingly, a unified communication that provides semantic translation between ERs knowledge enables semantic interoperability and mutual understanding of the exchanged information.

Figure 3.1: Example of semantic ambiguity.

3.2.2 Semantic translation

Semantic translation is defined as the process that "attempts to render, as closely as the semantic and syntactic structures of the second language allow, the exact contextual meaning of the original" [130]. In the literature, serval works have addressed ontology translation from both syntactic and semantic point of view but tend to focus more on the syntactic translation since its automation is easier [131]. In fact, semantic translation is a more difficult task because it requires finding relationships and mapping rules about the meanings of concepts from one ontology to another. Semantic translation depends on merging two ontologies and defining the mapping between them. Ontology merging consists of obtaining a new ontology from the integration of different ontologies. Ontology mapping implies defining relationships between the classes of the merged ontology such that semantics between classes can be matched. More accurately, it shows how the knowledge represented with the source ontology can be transformed using the target ontology. It can be done by implementing a formal inference on a merged ontology of the source and target ontologies. The possible semantic mappings are "subClassOf", "subPropertyOf", "sameClassAs", and "equivalentTo".

The semantic translation must be distinguished from the ontology mapping. Ontology mapping is the process of finding correspondence between concepts from different ontologies. It is a preprocessing step for enabling semantic translation of two ontologies [131]. The mapping between semantics is exploited to resolve semantic interoperability issues.

In the literature, semantic translation is addressed in different research. In [132], a survey and analysis of ontology management operation (mapping, matching, integration, etc.), algorithms, and tools are presented. Multiple approaches have been advanced to match information expressed in different terminologies in an ontology framework [133]. To the best of our knowledge, there is still a lack of addressing semantic translation of the information to be exchanged between ERs in the context of disaster response.

Bicer et al. [134] propose AMEF (Artemis Message Exchange Framework) that provides a semantic mediation among healthcare institutes. This mediation is done through a mapping tool that produces a mapping definition to transform a source ontology into a target ontology. For this purpose, an OWL ontology mapping tool was developed in order to allow semantic mappings among distinct ontologies. Then, the mapping definition is used by AMEF to automatically transform the source ontology message instances into target message instances. However, this engineering approach is only applicable in case of information exchange across healthcare institutes.

Real et al. [135] formalize domain-specific terminologies from the UK Civil and Protection Terminology lexicon. To do so, some of the most common terms that UK agencies use in emergency response scenarios are gathered and an extension for WordNet is developed. Then, a domain-aware semantic matching is proposed. The aim is to match words with similar meanings from various sources.

An automatic model transformation methodology is proposed in [136]. It combines semantic and syntactic checking measurements into the model transformation process. To do so, a semantic thesaurus has been created on the basis of WordNet. The mapping between source and target models is automatically done basing on an approximate value generated between two words. However, the chosen semantic meaning may not be exact to the word within a specific context of the source model. We believe that WordNet is not sufficient to be used in specific terminology such as ERs terminologies. In the case of military and first responder command and control applications, OntoNet is a platform for connecting sensors, services, and agents on the network [137]. It proposes a knowledge-based approach to message addressing and matching. In fact, the focus of OntoNet is on effectively matching messages and receivers and not on the semantic meaning of the message's content.

In the context of INTER-IoT (Interoperability of Heterogeneous IoT Platforms) project, SEMIOTICS (SEmantic Model-driven development for IoT Interoperability of emergenCy serviceS) aims to detect accident risks with trucks that deliver goods at the Valencia port area. To do so, Moreira et al. [138] present an interoperable framework architecture for the integration of different IoT architectures. Authors propose the Inter-Platform Semantic Mediator (IPSM) software tool that enables real-time semantic translations following five steps: make semantics explicit, define a central modular ontology, define uni-directional alignments between the central ontology and ontologies of communicating artifacts, and establish communication architecture in order to facilitate translations between ontologies. More accurately, it consists of establishing alignment between two well-known ontologies: W3C Semantic Sensor Network (SSN) and Smart Appliances REFerence (SAREF). To do so, the mapping between these ontologies are performed followed by the semantic translation. In fact, the mapping between SSN and SAREF follows a logical sequence of ontological analysis of their TBox to create a new SAREF-based ontology. That is to say, authors start by the specification of the possible mapping and rules in natural language to show how an instance of the source ontology can be represented with the target ontology, and then they implement these mappings. IPSM create a SPARQL query for each rule in order to find instances and generating a new ontology instance.

If we project this work in our context, the automatic mapping between ontologies cannot be used to define equivalences between stakeholders' knowledge. The semantic translation of ERs exchanged information is a very delicate process; it necessitates an accurate mapping between stakeholders' concepts to guarantee the exact meaning of the exchanged information. Accordingly, we propose a semi-automatic process that starts by defining manually the semantic mapping between stakeholders ontological modules by referring to emergency experts, then the semantic translation of the message is done automatically based on the defined mapping.

3.3 Ontology-driven semantic interoperability approach: PROMES

In this context, we propose an ontology-based messaging service called PROMES for "POLARISC Ontology-Based Operational Messaging Service" in order to ensure timely, accurate, and semantically meaningful information among ERs. It is responsible for ensuring consistent and semantically enhanced information exchange among ERs. The main purpose of PROMES is that each stakeholder will receive the message according to his own vocabulary and with his own semantics. The architecture of PROMES is presented in Figure 3.2.

In order to share information, stakeholders that use different vocabularies must be able to translate data from one ontological framework to another. Accordingly, in case there is an information exchange between two stakeholders from different ERO, PROMES is used on-demand by POLARISC mediator which is connected to the POLARISC platform, to perform the semantic translation of the information to be exchanged. The semantic translation of the message content is based on the semantic relationships that exist among stakeholders' ontological modules as defined in POLARISCO.

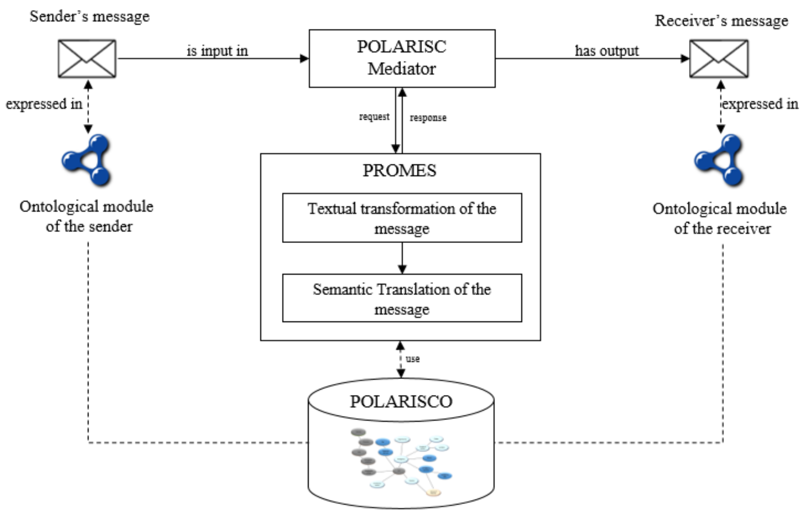

Figure 3.2: PROMES architecture.

The message-driven mechanism is divided into four steps as shown in Figure 3.3; message input by the user, textual transformation of the inputted classes, message validation of the textual transformation by the user, and then the ontology-based semantic translation of the message. The consistency of the semantic translation of the message depends mainly on the syntactic features of the inputted classes.

In fact, there are various types of messages to be exchanged among ERs at the operational level such as departure message, arrival message, backup request message, progress report message. Concerning the French EROs, it should be noted that there is a predefined structure to compose each message in a succinct, but clear way by providing a means for standardizing these latter in order to guarantee the clarity of the information (Table 3.1). A message should be in the form "I am, I see, I do, and I demand". More accurately, in each message, stakeholder should start by presenting his localization (I am), secondly, he mentions the type of the incident, the implicated victims and their states (I see), thirdly, he reports the progress of the intervention (I Do) and finally he points out whether there is a need to request backup or the resources are sufficient (I demand). Table 3.2 shows an example of ERs exchanged information. One can conclude that the messages are composed of technical words and abbreviations that are mainly related to the nature of the ERO. It is not obvious that another stakeholder from another ERO can decrypt the message correctly. Furthermore, the input of the message is a very delicate exercise, stakeholders should not mislead the inputted text. As a direct result, the message input time is longer.

To tackle these problems, we developed a guided user interface (GUI) that respects the predefined structure of each message (see section 1.3.6). Once the type of the message is chosen, the user is guided to structure the message class by class. These classes proposed by the GUI are loaded from POLARISCO. In such a way, the message editing process takes less time since it is selected class by class and not manually written. Moreover, this oriented way of message's edition enables the effectiveness of the syntactic form of the message and guarantees the effectiveness and accuracy of the semantic translation of the message.

Table 3.1: Structure of ERs message.

Ontology	Number of Classes
« I am »	The validation or modification of the address.
« I see »	The nature of the incident, number of victims...
« I do »	The evolution of the intervention.
« I demand »	The backup request or "sufficient relief".

Table 3.2: Examples of ERs messages.

CODIS 68 FPT1 Ribeauville left, agent 0.1.7.
CG 68 VSAV1 Turckheim on site.
CS 68 VSAV1 Turckheim present in AC Turckheim.
CODIS 54 VSAV 2 Mteropolis intervention.
AVP Choye D474, 1VL, 2 implicated, 1 indemne, 1BL, GN SLL, Sufficient relief.
CODIS, CSAV Gy transport 1 BL non medical to HC Gray, first aid report sento to CRRA15.

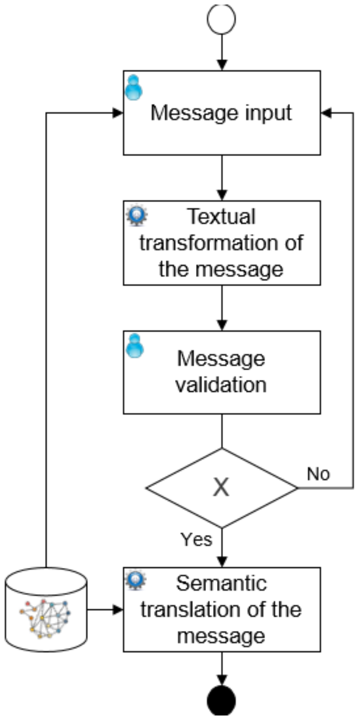

Figure 3.3: PROMES process.

3.3.1 The message module of POLARISCO

In this work, the message ontological module has been defined based on EDXL standards [139]. These latter are a suite of standards developed by the joint efforts of the Department of Homeland Security (DHS) and the emergency management technical committee of the Organization for the Advancement of Structured Information Standards (OASIS). They have been used in multiple disaster management applications. EDXL is a collection of messaging standards designed to facilitate emergency information sharing and data exchange across EROs. Each standard is related to a particular aspect of the emergency domain, including Common Alerting Protocol (CAP), Distribution Element (DE), Hospital AVailability Exchange (HAVE), Resource Messaging (RM), Situation Reporting (SitRep), and Tracking of Emergency Patients (TEP). The aim is to enable interoperable information exchange between ERs on the field and the operational centers. The office for interoperability and compatibility (OIC) studied a hurricane scenario to show the use of EDXL standards to enable interoperability during emergency response.

The EDXL standards were used before as the basis for ontology development. After the study of the existing ontologies in chapter 2, we found that there are two ontologies that define knowledge about stakeholders' communication; EDXL-RESCUER ontology and PS/EM ontology. EDXL has been applied already in these two ontologies.

EDXL-RESCUER ontology is the conceptual model of the RESCUER project that represents information exchange among legacy systems for emergency and crisis management

[53]. It is based on EDXL-DE and EDXL-CAP for the creation of alerts addressed to persons affected by a disaster. It is a semantic model of EDXL standards for message enveloping (EDXL-DE) and for alerts (EDXL-CAP). It defines mainly message type, status, scope, sender, certainty (possible, likely, observed, certainty unknown), severity (moderate, minor, severe, extreme, severity unknown), and urgency (future, past, immediate, expected, urgency unknown). The EDXL-RESCUER ontology is not yet used in the real world.

PS/EM ontology is used to provide a foundation for semantic interoperability between different PS/EM communication systems [98]. It is developed basing on the four EDXL standards; EDXL-DE, EDXL-RM, EDXL-HAVE, and EDXL-CAP. Specifically, PS/EM defines the different types of messages; alert message (initial alert, update alter and cancel alert), alert acknowledgment message and alert rejection message. Furthermore, it defines incident response activities such as evacuation and finding shelters.

In fact, EDXL-RESCUER and PS/EM ontologies focus only on alert messages and do not cover other types of communication among ERs. To define the message module, we reused classes from the PS/EM ontology rather than EDXL-RESCUER because of the fact that PS/EM ontology was grounded in the BFO upper-level ontology. Accordingly, POLARISCO and PS/EM ontology follow the same vision for defining what exists. The reused classes from PS/EM ontology are marked in the following figures with the prefix EDXL.

In POLARISCO, we define an “edxl: message” as a “cco: information bearing artifact” (see Figure 3.4). Moreover, a message has a sender and a receiver. It can be sent simultaneously to multiple receivers. Each of the transmitted messages is then a distinct “cco: information bearing artifact”. However, the content of the message is the same. For this purpose, we defined the content of the message as a “cco; information content entity”, where each information bearing artifact is related to the relevant information content entities using the “bearer of” relationship. When the message is semantically transformed and sent to different receivers, this results in different information content entities. The fact that these are all transformations of one single message is captured by using a single ID, defined as a “code identifier”.

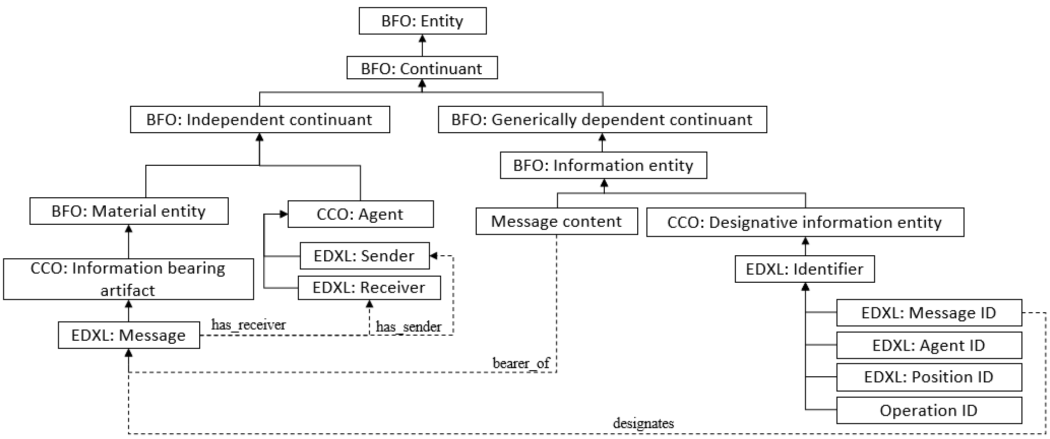

Figure 3.4: Definition of a message in POLARISCO.

In disaster response, there is a classification of messages in order to standardize communication among stakeholders. The messages are classified into three types basing on their objectives including “informative message”, “request message” and “response message”. “Informative message” includes “information message”, “alert message”, and “report message”, and so forth. The aim of “information message” is to inform EROs of an event in a formal manner. It can be about the notification of an emergency plan launching, departure or arrival time of agents on the disaster scene and so on. Then, the “request message” is about asking for additional resources, information about updating the situation, or permission. For instance, the commander of the on-going operation on the disaster scene decides that the available resources are not enough to effectively manage the situation and request supplementary resources or backup. A “response message” concerns a “request message”. For this purpose, we used the relationship “is_about” to relate these latter as shown in Figure 3.5.

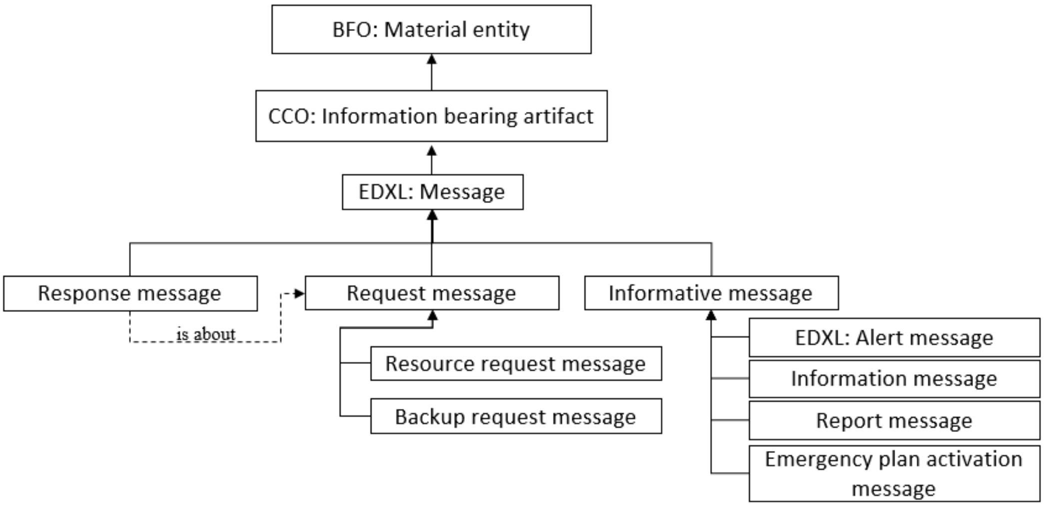

Figure 3.5: The different possible types of a message.

In addition, a message is characterized by some features that can be perceived as “quality” in BFO. In fact, “quality” is defined in BFO as a specifically dependent continuant that depends or inheres in an entity at all and is fully exhibited or manifested or realized in that entity. Accordingly, we defined the state (“treated”, “untreated” or “ongoing”), the confidentiality (“public”, “private” or “limited”) and the degree of criticality of the information to be exchanged (“extreme”, “moderated” or “secondary”) as subclasses of “bfo: quality”. Then, we associate a message to the defined qualities using the relationship “has quality”. Figure 3.6 shows the mentioned classes.

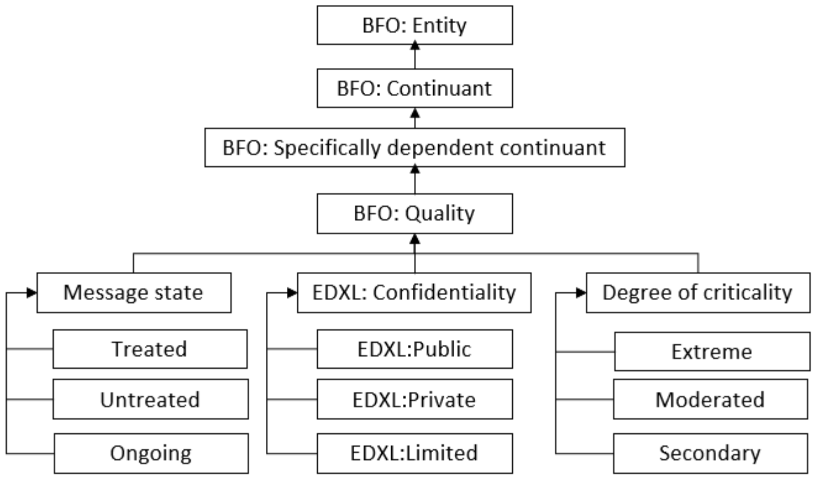

Figure 3.6: The different qualities of a message.

3.3.2 Message-Driving Formalism and definitions

In this subsection, we present a formal definition of an ontology and a message that will be used when elaborating the proposed algorithms.

Definition 1: An ontology O is formally defined as a 4-tuple: $0 =< C, R, A_x, I >$ where:

C represents the set whose members are the classes in the ontology.

R is a set of relations that exist between these classes, where $R \subset CxC$.

A_x is a set of axioms.

I is a set of instances.

Definition 2: The set of ontological modules is denoted by M, where $M = \{m_1, m_2 \ldots m_n\}$, and defined as a 4-tuple:

$m =< C_m, R_m, A_{xm}, I_m >$ Where:

$C_m \subseteq C$

$R_m \subseteq R$

$A_{xm} \subseteq A_x$

$I_m \subseteq I$

Definition 3: A modular ontology O is the integration [2] of different ontological modules

[2] Ontology integration, or interrelations, means to put together (interrelate) multiple ontology modules to compose a new ontology.

m and the relations that exist among those modules where: $O = \bigcup_{i=1}^{n} m_i$

Let R_{intra_m} be the set of intra-modules relations.

Let R_{inter_m} be the set of inter-module relations.

$R = R_{inter_m} \cup R_{intra_m}$

Definition 4: Each ontological module represents the vocabulary of an actor. We write A for the set of all actors Where:

$\forall a_i \in A$, there is $m_i \in M$ such that:

$f : A \rightarrow M$

$a_i \rightarrow m_i$

Definition 5: An act of communication between two actors is represented by a message. A message msg is defined as 5-tuple $< msgType, sender, receiver, msgIC_{source}, msgIC_{target} >$ Where:

msgType represents the type of the message such as $msgType \in MSGType$.

sender identifies the actor source of this message such as $sender \in A$.

receiver identifies the actor target of this message such as $receiver \in A$. We consider that a receiver can be one or more.

msgIC represents the information content of the message which is composed of a set of classes and instances from the ontology O such that:

$msgIC_{source}$: information content of the sender's message where $msgIC_{source} \subset C_{m_{source}} \cup I_{m_{source}}$

$msgIC_{target}$: information content of the receiver's message where $msgIC_{target} \subset C_{m_{target}}$

Definition 6: The function TRs yields the semantic transformation of the message's information content:

TRs $(msg(msgIC_{source})) \rightarrow (msg(msgIC_{target}))$

In what follows, we apply these generic definitions to POLARISCO and PROMES:

The modular ontology O = POLARISCO

$M = \{PCC, firefighters, police, healthcare\ units, gendarmerie, public\ authorities, message, healthcare\ resources\}$

$POLARISCO = m_{PCC} \cup m_{firefighters} \cup m_{police} \cup m_{healthcareUnits} \cup m_{gendarmerie} \cup m_{publicAuthorities} \cup$

$m_{message} \cup m_{healthcareResources}$

$C = \{\ulcorner operation \urcorner, \ulcorner agent \urcorner, \ulcorner mean \urcorner, \ulcorner mean\ type \urcorner, \ulcorner action\ center \urcorner, \ulcorner degree\ of\ criticality \urcorner ...\}$

$Rinterm = \{\ulcorner realized\ in \urcorner, \ulcorner caused\ by \urcorner, \ulcorner has\ role \urcorner, \ulcorner is\ part\ of \urcorner, \ulcorner use \urcorner ...\}$

$Rintram = \{\ulcorner is\ equivalent\ to \urcorner, \ulcorner belongs\ to \urcorner, \ulcorner supervises \urcorner ...\}$

$A = \{Firefighters, Police, healthcareunits, Gendarmerie, Public\ authorities\}$

$msgType = \{\ulcorner response\ message \urcorner, \ulcorner resource\ request\ message \urcorner, \ulcorner information\ message \urcorner, \ulcorner alert\ message \urcorner, \ulcorner report\ message \urcorner, \ulcorner Arrival\ message \urcorner, \ulcorner departure\ message \urcorner ...\}$

3.3.3 Textual transformation of the message

PROMES provides a textual transformation of the set of the inputted classes so that the message can be easily interpreted by other stakeholders considering the structure of the message as seen at the beginning of this section. The aim is to reduce the ambiguity of the message by adding more information. To do so, we propose a textual transformation algorithm (TT) that concatenates the inputted classes in a clearer way. The input of PROMES is a list of classes and instances that belongs to the sender's ontological modules. As a first step, this list is transformed into text using the TT algorithm. In fact, this latter takes into account the predefined messages' structures of EROs. In particular, it uses the set of selected terms to compose the message by adding text to relate them according to the predefined structure (see Figure 3.7). The output of this step is a message written in formal language rather than a list of non-related technical terms and acronyms. It is a first step towards extending the message and make it more understandable by the rest of the stakeholders.

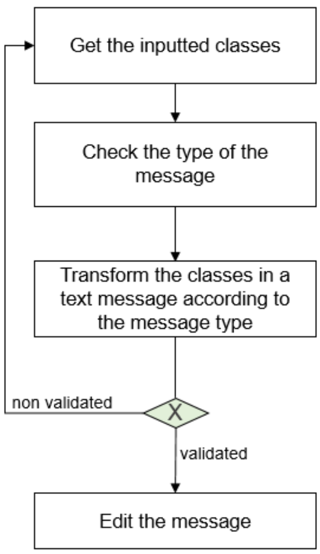

Figure 3.7: The different steps of the textual transformation process.

3.3.4 Semantic translation of the message

The development of semantic translation depends on the ontology mapping. Accordingly, to perform the semantic translation, we need to carry out the semantic mapping in order to address the heterogeneity gap between stakeholders' knowledge by identifying the related concepts. The proposed approach consists of two steps as shown in Figure 3.8; the mapping between the ERs ontological modules and the semantic translation of the message.

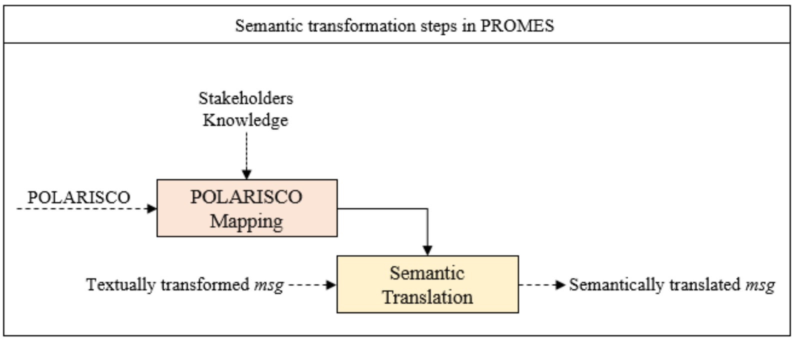

Figure 3.8: The ontology-driven semantic transformation approach.

3.3.4.1 The mapping between stakeholders ontological modules

As seen in chapter two, the use of top-level ontologies facilitates the integration of different domain ontologies defined in their terms and thereby promotes interoperability of the associated data. Once the stakeholders modules are merged in one ontology, POLARISCO, the next step is to perform the mapping between these latter. We consider one possible kind of mapping between classes, which is "equivalentTo". It is about representing the equivalences between the classes of the ontology module of stakeholder 1 and stakeholder 2. The semantic mapping is done in collaboration with emergency experts to ensure the effectiveness of the defined equivalence relationships. These defined relationships are the keystone of the semantic translation; they will facilitate the interpretation of the information by stakeholders. Figure 3.9 shows an example of equivalence relationships between firefighters module and healthcare units module. For instance, an absolute emergency "AE" for firefighters is equivalent to "P0" for healthcare units. These relationships will guide how the input message formalized with the source ontology of the sender can be transformed in message represented with the target ontology of the receiver.

When defining the mapping between the different classes, we formulated a SPARQL query in order to check the efficiency of the defined equivalent classes in each direction. This step aims to find possible conceptual errors that enables the early correction of the mappings before the implementation step.

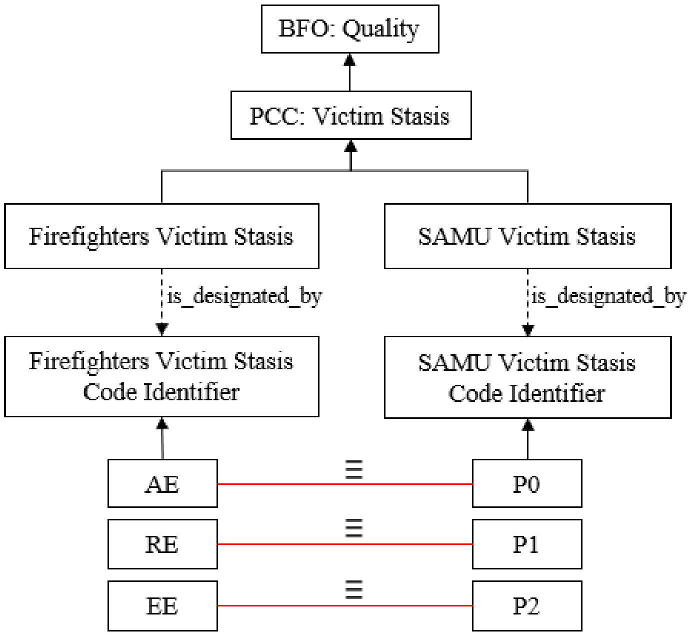

Figure 3.9: Example of mapping between firefighters and healthcare units knowledge.

3.3.4.2 The semantic translation algorithm

If the sender and the receiver don't belong to the same ERO, PROMES proceeds to the semantic translation. To do so, we propose a semantic translation algorithm (ST) that transforms the list of terms, selected by the sender, according to the ontological module of the receiver. For each term of the information content source ($msgIC_{source}$), ST checks if it is a class or an instance in POLARISCO. If it is an instance, the algorithm gets its class in order to perform the rest of the transformation. The, ST verify if the class belongs to PCC module. if it is the case, the class remains the same because the different EROs share the same term. If it is not, ST checks its equivalent class. If there is an equivalent class that belongs to the module of the receiver, the class will be substitute by its equivalent class. In case there is no equivalent class found defined in POLARISCO, ST doesn't stop at this level. Contrariwise, it adds more semantic in the message by enriching it using the class annotations (definition or/and acronym's meaning). The annotations can be used to reveal the meaning of the term even though the EROs don't use it, they can understand what is it about based on its definition. In case the class has no annotation, we search for the annotation of its superclass. The pseudo-code of the ST algorithm is provided in Algorithm 1.

Algorithm 1 Semantic Translation

Input:
$msgIC_{source}$= $\{ic_{source1}, ic_{source2} \ldots ic_{sourcen}\}$: set of terms that compose the sender's message
$POLARISCO$= $\{m_{pcc} \ldots\}$: The global ontology
C: set of the ontology's classes
Output:
$msgIC_{target}$: set of terms that compose the receiver's message
Variables:
ic'_{source}: class
ec: equivalent class
sp: superclass
A: set of annotation
$indiv$: instance of a class c **begin**

```
    Initialize a list msgIC_target ⟵ {}
    indiv = null
    ic'_source = null
    while msgIC_source ≠ ∅ do
        foreach ic_source ∈ msgIC_source do
            find(ic_source) in POLARISCO
            if ic_source ∈ C then
                ic'_source ⟵ ic_source
            else
                ic'_source ⟵ getClass(ic_source)
                indiv ⟵ ic_source
            end
            if ic'_source ∉ m_pcc then
                ec ⟵ getEquivalentClass(ic'_source, m_receiver)
                if ec ≠ null then
                    msgIC_target ⟵ indiv + ec
                else
                    A ⟵ getAnnotation(ic'_source)
                    while A = ∅ do
                        sp ⟵ getSuperClass(ic'_source)
                        A ⟵ getAnnotation(sp)
                    end
                    msgIC_target ⟵ ic'_source + indiv + A
                end
            else
                msgIC_target ⟵ ic_source
            end
        end
    end
    return (msgIC_target)
end
```

To summarize, the ST algorithm is mainly about five steps as shown in Figure 3.10:

1. Find the term in the ontology.
2. Get its class, if it is an instance.
3. Check if the class doesn't belong to PCC module.
4. Get its equivalent class that belongs to the ontological module of the receiver and substitute them.
5. If there is no equivalent class, get its annotation and add it in the message.
6. If it has not any annotation, get the annotation of its superclass and add it in the message.

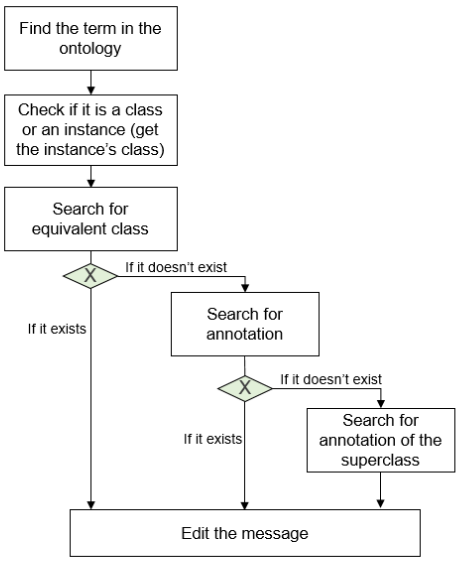

Figure 3.10: The different steps of the semantic transformation process.

3.3.5 PROMES components interaction

Before the implementation of the proposed approach, we elaborated a sequence diagram to demonstrate the interactions that exist between the different components and to ensure that there are no logical problems. To send a message, the stakeholder selects the type of message and inputs the according classes using the GUI. These classes are loaded from POLARISCO. The output of the edition step is a set of classes selected by the sender. The next step is the textual (or structural) transformation of the message from a set of classes to a textual message using TT algorithm based on the pre-defined structure of ERO messages. Once the user validates the proposed textual transformation by PROMES, POLARISC mediator checks if the sender and the receiver belong to the same ERO and subsequently share the same ontological module. If it is not the case, POLARISC mediator uses PROMES to semantically transform the message according to the vocabulary of the receiver. ST algorithm transforms information expressed according to the ontological module of the sender into equivalent information defined using the ontological module of the receiver. Figure 3.11 shows the interactions sequence among the GUI, POLARISC mediator, PROMES, and POLARISCO.

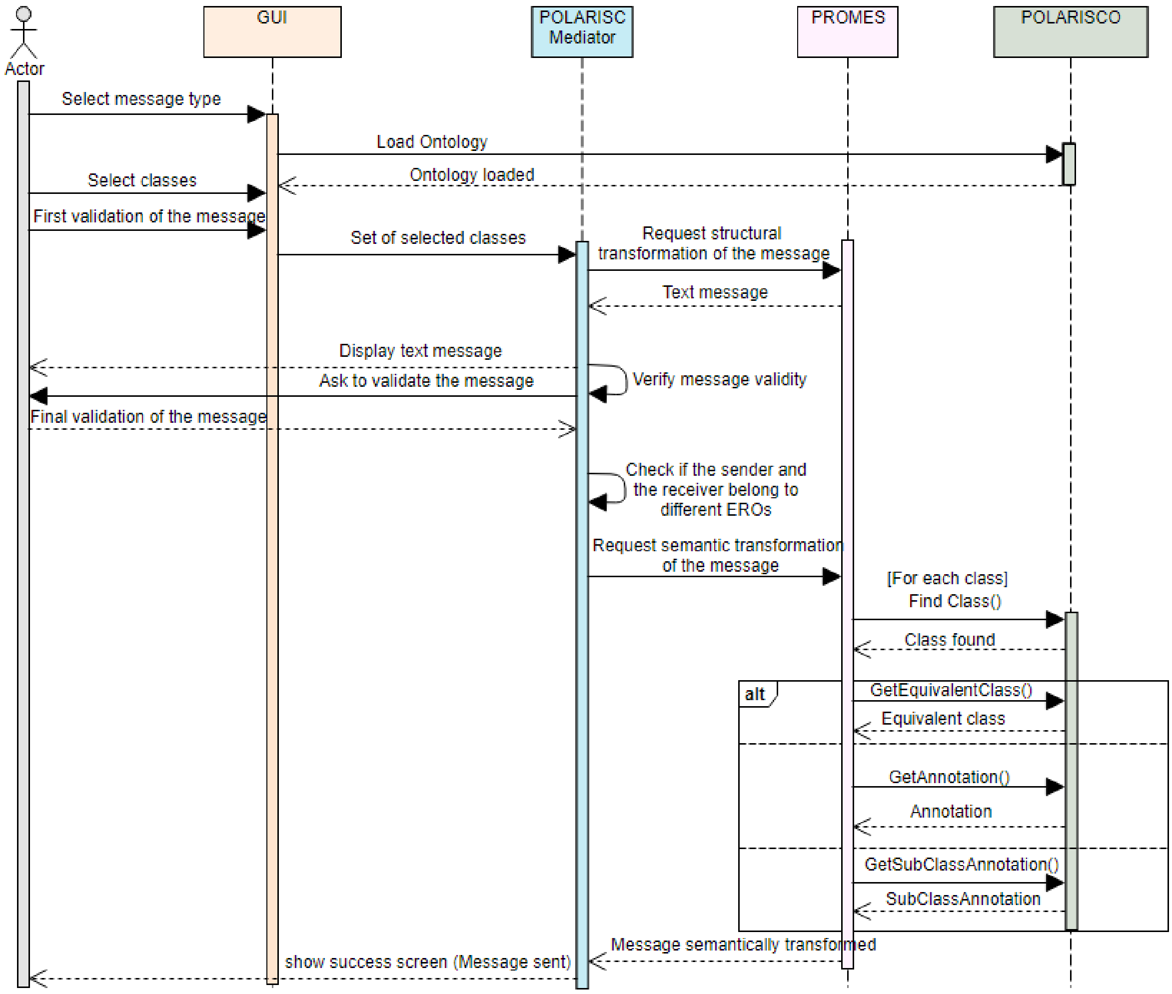

Figure 3.11: Sequence diagram of the message transformation process.

3.4 Implementation and use-case evaluation

To build the proposed ontology-driven messaging service prototype, PROMES, Java and Eclipse IDE are used. Maven is used for managing the project. OWL API has been applied to manipulate the ontology. It is a Java API used for the creation and manipulation of OWL ontologies when developing ontology-based applications. In addition, Java Swing is used to implement the GUI. Since this is not a technical report about the developed application, we will not present the engineering details. A use-case is presented in the following to show a scenario test in order to evaluate the functioning of PROMES.

Let's consider an example of an act of communication between firefighters and healthcare units. Once the firefighters' unit is on the field, they figure out that they don't have enough vehicles of succor and assistance to victims (VSAV). Accordingly, they need backup from healthcare units to handle the rescue of a large number of victims in a critical situation. The firefighter commander (FC) uses PROMES which is integrated into the POLARISC platform as a communication tool.

FC uses the PROMES guided user interface (GUI) and starts by choosing the receiver and the type of the message to send, which is a resource-request message in this case. Then, FC chooses the appropriate terms step by step as required by the GUI as shown in figure 3.12. Once the terms are selected, the textual transformation of these latter is done. It is up to the firefighter commander to validate the result of this first step. After the validation, the semantic transformation is started.

For the current use-case, PROMES starts the checking process class by class (see Figure 3.13 and 3.14). First, the term "TA75" is an instance so it looks for its class ("Terrorist Attack"). "Terrorist Attack" class belongs to PCC module. Hence, PROMES keeps the same term. Second, "VSAV" is a subclass of "firefighters' vehicle" and there is no equivalent class in the healthcare units module, so PROMES adds the annotation of VSAV to explain the meaning of the acronym and its definition. Third, "victims'rescue" is a subclass of "act" and belongs to PCC module so it remains unchangeable. Then, "AE" (Absolute Emergency) is a subclass of "firefighters' victim stasis code identifier" which is equivalent to the subclass of "SAMU victim stasis code identifier" "P0". Therefore, "AE" is substituted with "P0". The action center of the ongoing operation is called "AC_PS_75" by firefighter while it is called "P_75" by healthcare units. Thus, "AC_PS_75" is replaced by "P_75". We can notice that the semantically transformed message is extended and improved so it can be less ambiguous when received by the healthcare units (see Figure 3.15).

3.5 PROMES validation

In order to validate the proposed approach, the performance of PROMES is analyzed in terms of efficiency and accuracy following the validation approach presented in [140] and [141]. It consists of describing the accuracy and the efficiency of a set of messages produces by the proposed approach. According to [140], translation accuracy is to "correctly translate and describe semantic information of an input message in the form of a target message", and the translation efficiency is to "minimize communication delays by efficient translations of many semantic messages". Hence, the translation efficiency is evaluated in terms of processing complexity.

To do so, as a first step, we defined a set of 100 test messages in the form of a message source and its planned to be translation output. Then, we tested each message and we compared the output message versus the expected result. Each information content of the input

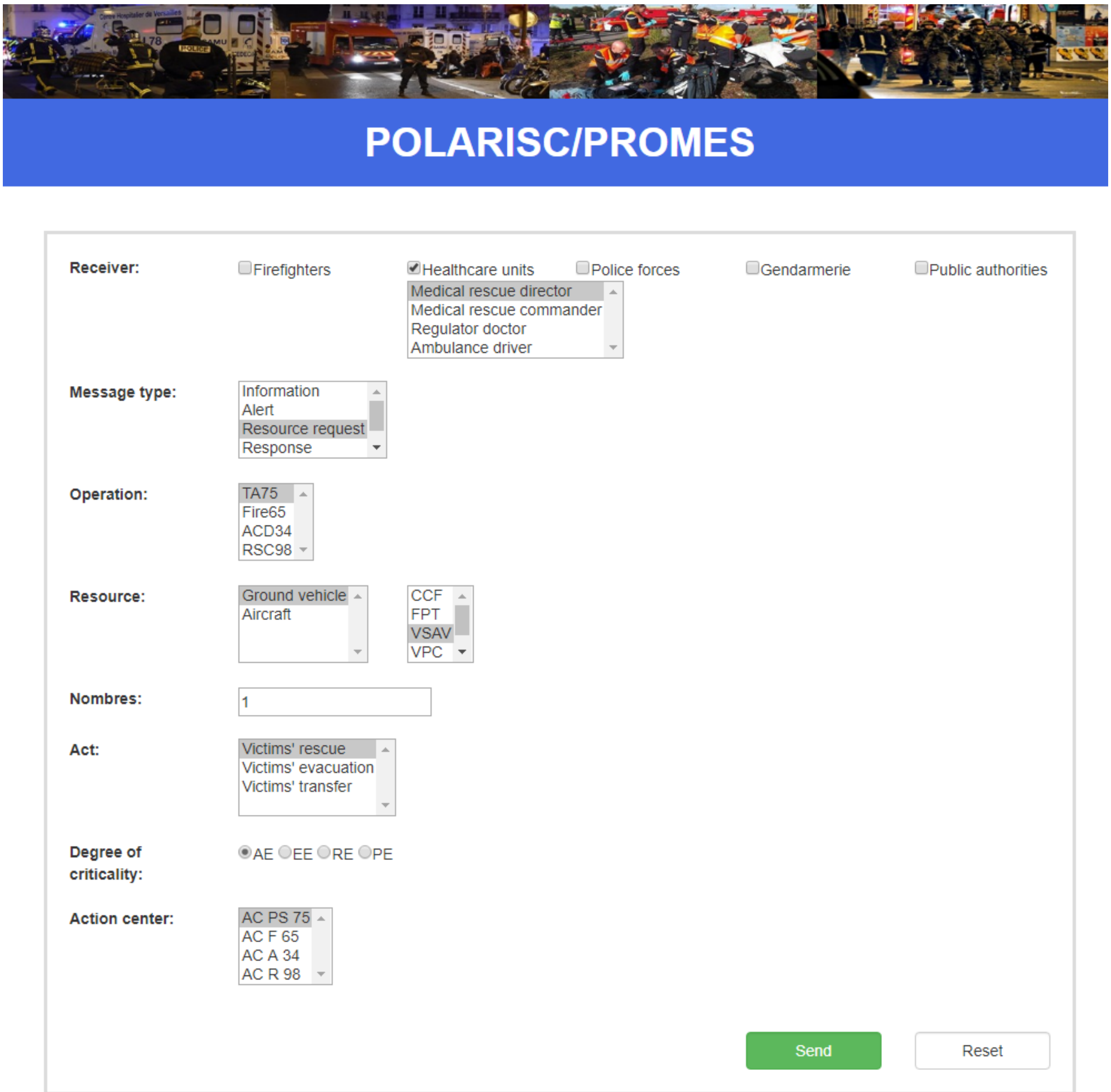

Figure 3.12: PROMES' Guided User Interface (GUI).

Information content source	{TA75, VSAV, victims' rescue, AE, AC PS 75.}
Output of TT	**TA75:** we needs **VSAV** for **victims' rescue** in **AE** in **AC PS 75**.
Output of ST	{TA75, VSAV, Vehicle of Succor and Assistance to Victims, VSAV is a firefighters vehicle reserved for victims' first aid , P0 , P 75.}
Information content target	**TA75:** we needs VSAV***(Vehicle of Succor and Assistance to Victims)** for **victims' rescue** in **P0** in **P 75**. ***VSAV is a firefighters vehicle reserved for victims' first aid.**

Figure 3.13: Message transformation example.

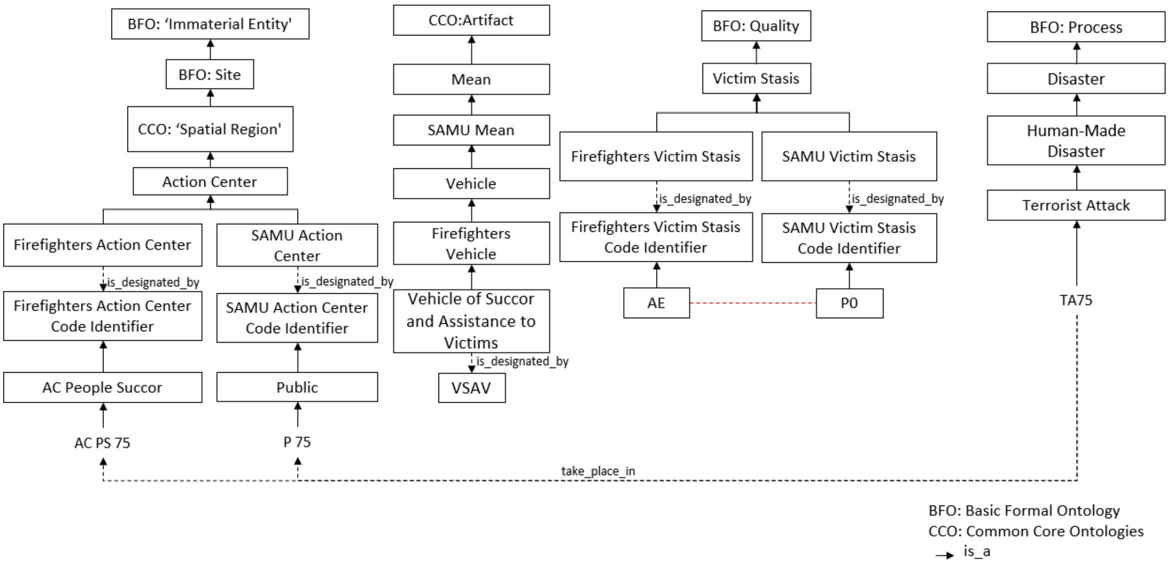

Figure 3.14: A sample part of an instance of a terrorist attack.

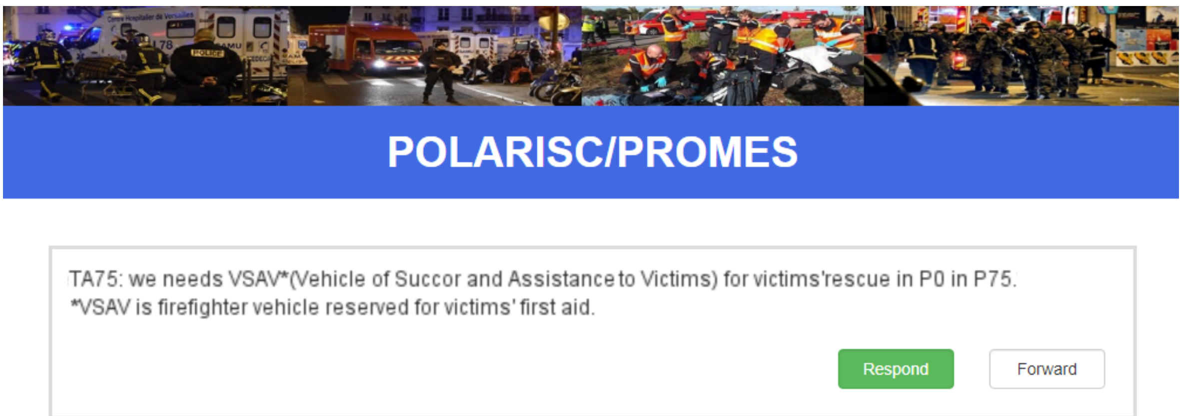

Figure 3.15: The received message.

message msgICsource, was transformed using the TRs function $(TRs(msg(msgIC_{source})) \rightarrow (msg(msgIC_{target})))$. In fact, we tested the proposed approach with the use of the GUI (1) and without it (2). In order to measure the semantic translation accuracy of the test messages, we calculated the number of output messages that match with the expected ones regarding the total number of test messages using the following formula:

$$\frac{No.ofmatchedtoexpectedtranslationoutputcorrectsemantictranslationoutput}{No.oftestmessages} \tag{3.1}$$

As shown in Figure 3.16, the results showed that using the GUI (1), the semantic translation is 100% accurate. In fact, there are no cases of untranslatable and syntax errors because the GUI input relies on well-defined classes loaded from POLARISCO. However, without the GUI (2), only forty-seven from one hundred tested messages were accurate. These results are due to the manual input of the message. Stakeholders may not make intention the correct spelling of each world and especially the acronyms ones; a lower case letter is written instead of an upper letter or the opposite handicap the semantic translation process. Thus, the use of the GUI guarantees the accuracy of the output message because it loads classes from the ontology in order to avoid syntax errors that may impede the semantic translation process. Using the GUI, all messages were syntactically correct. In addition, the bi-directional verification of the defined equivalent classes in the ontology mapping step guaranteed the semantic translation accuracy.

As expected, the time of the input using the GUI is lower than the manual input as shown in Figure 3.17. However, as the messages get larger, the input time is longer. In fact, like any new software application, the final users, ERs in this context, need to be formed to use the application. We did a test with stakeholders to get their feedback about the use of the proposed GUI. For this, we asked one stakeholder to input the same message ten times using the GUI and then to manually write the message. We can see that the input time is decreasing each time as depicted in Figure 3.18. Consequently, ERS preferred the use of the GUI because it will save time during operational response and guarantee an accurate semantic translation of the exchanged information.

Concerning the semantic translation efficiency, it was measured according to the total processing time of PROMES (see Figure 3.19). We found that the processing time depends mainly on the number of classes that compose the message that doesn't belong to the PCC module and should be translated. One can notice that the processing time can be a bit longer than usual due to the fact that the message is semantically richer.

In this subsection, we showed that the use of PROMES enables an efficient and accurate semantic translation of ERs exchanged information and subsequently empowers semantic interoperability among the involved stakeholders in the process of operational disaster response.

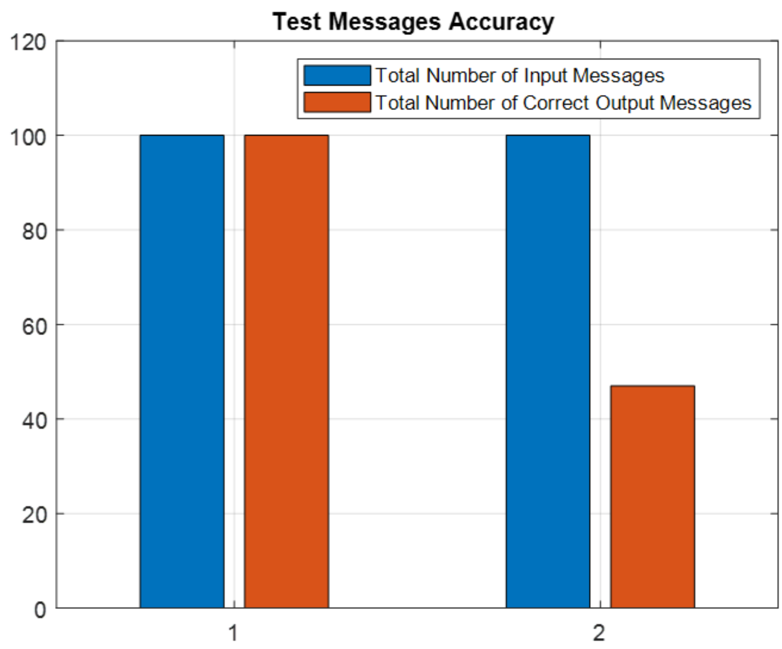

Figure 3.16: Results of the semantic translation accuracy.

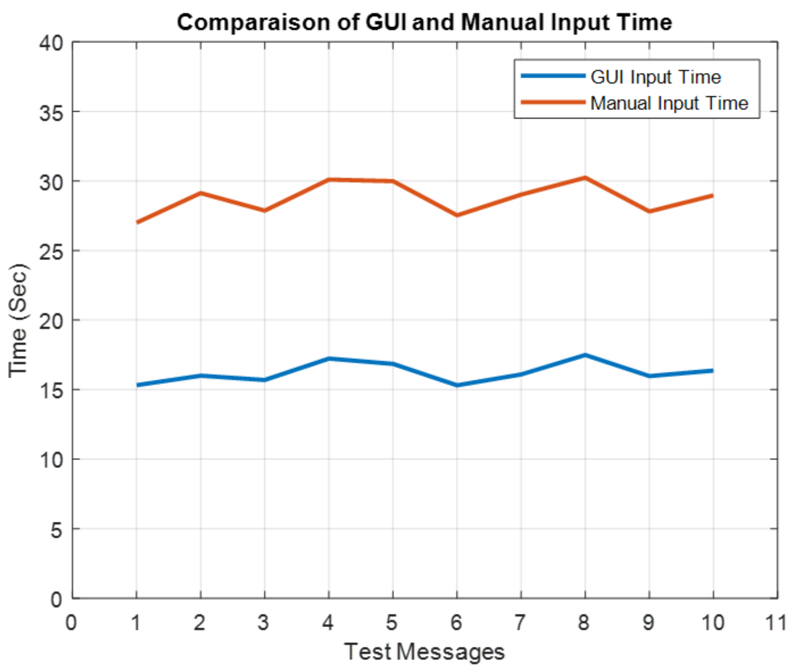

Figure 3.17: Results of GUI and manual input time.

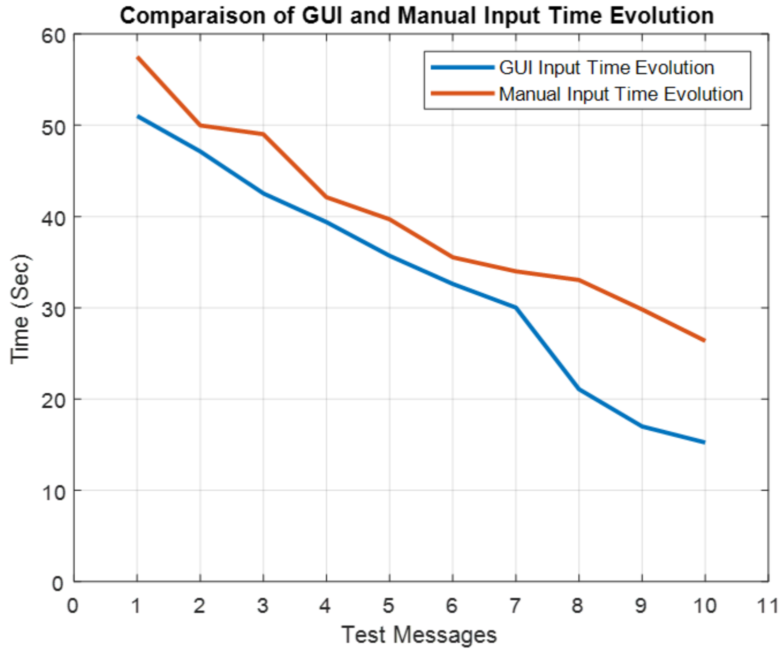

Figure 3.18: Results of the input time of the same message by the same stakeholder.

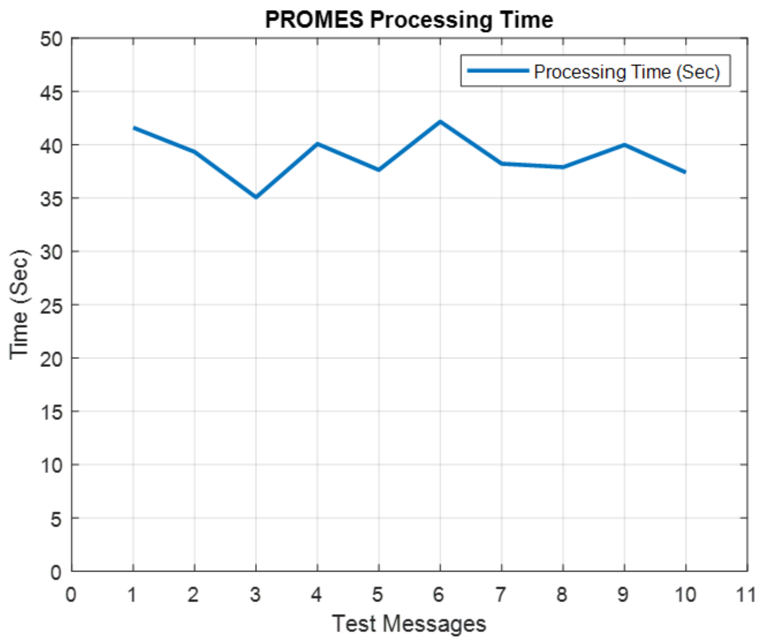

Figure 3.19: Results of the semantic translation efficiency.

3.6 Conclusion

ERs often underperform due to a lack of proper communication and information sharing among them. It is much easier to enable communication between two stakeholders from the same ERO that use the same vocabulary where the terms have the same meaning and interpretation. But the fact that vocabularies are different makes communication more difficult. Accordingly, there has been a considerable increase in semantic obstacles that hinder the sharing of information and become one of the main issues for efficient knowledge sharing. To tackle these problems, we must resort to semantic translation to avoid ambiguities and misunderstandings during information exchange in order to achieve semantic interoperability among ERs. In this chapter, we proposed PROMES an ontology-based messaging service. It a message-driven mechanism that ensures semantic translation of the knowledge expressed using the source ontology of a stakeholder a into knowledge expressed using the target ontology of a stakeholder b. The proposed service can greatly improve the efficiency of communication among stakeholders during disaster response. It enables information tractability and consolidation and ensures semantically interoperable information exchange by providing a mapping among stakeholders' vocabularies. Using PROMES, it becomes possible for two ERs from different EROs to communicate meaningfully and with less ambiguity. It delivers timely and accurate information to each stakeholder. The proposed approach is evaluated and validated, and the numerical results demonstrate its efficiency and robustness so that it can be used by ERs.

Chapter 4

PROOVES: Multi-criteria decision support for victims evacuation

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4.1 Introduction

Disasters often create a large number of victims. These victims can be classified as injury-free sufferers and wounded victims. Injury-free victims are transferred to a temporary shelters and wounded victims are rapidly transported to hospitals to receive an appropriate medical treatment for their injuries. The evacuation of wounded victims should be as effective as possible in order to maximize the number of survivors. To do so, identifying the best hospitals to evacuate the victims is vital. In this chapter, we propose a multi-criteria decision support service as part of the POLARISC platform for the assessment of the most appropriate hospital to the victim's needs. The aim is to avoid hospitals' crowding and outpacing the capacity to effectively provide the best care to victims. The proposed approach considers the victim's medical needs, the dynamic updates of the resources' availability, and the victims' wait time in hospitals.

4.2 The process of victims' evacuation in France

The organization of the medical response of large-scale disasters in France is articulated around two interlinked and complementary emergency plans: NOVI plan and White plan (Plan Blanc). The NOVI plan, which is an updated version of the Red plan, is the reference plan for the on-site mass causality management. It is defined as "the implementation of a pre-prepared doctrine with means and personnel are likely to deal with the consequences of a natural, technological or social event causing or likely to cause mass casualties, so that the emergency response resources meet the acute increase in healthcare needs" [142]. It concerns the process of victims' extraction from the hostile environment, victims' triage and healthcare provision in and around the PMA (Medical Advanced Post), and resource mobilization.

Figure 4.1 depicts the process of deployment of the NOVI Plan. Specifically, once the victims are assembled in the victims' gathering point (PRV), they receive first aid and they are sorted under the authority of the chief medical officer in order to recognize who is the most urgently in need for receiving immediate care. Victims are classified based on their injury levels as either relative emergency (RE) or absolute emergency (AE). Victims with a relative emergency are transported to the PMA to receive instant medical care. Those who have an absolute emergency are transported immediately to a hospital. The evacuation resources can be firefighter rescue vehicles, ambulances, helicopters, and so on. The victims' transportation is managed by both firefighters and healthcare units. At the disaster site, this evacuation process is commanded by the medical succor director known by his French initials DSM who is an experimented doctor assigned by the healthcare units.

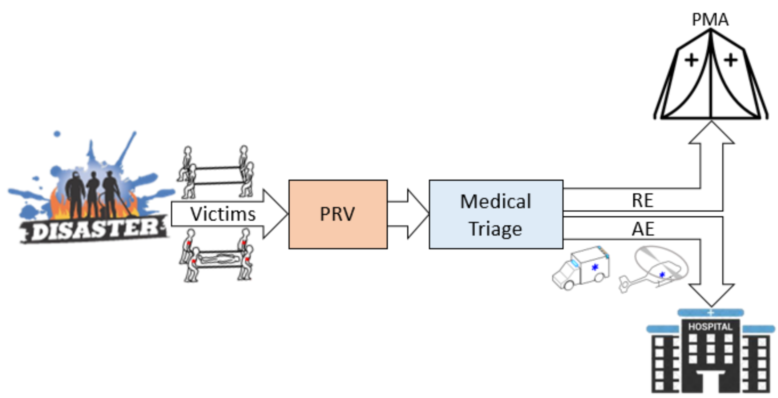


Figure 4.1: Process of the deployment of the NOVI Plan.

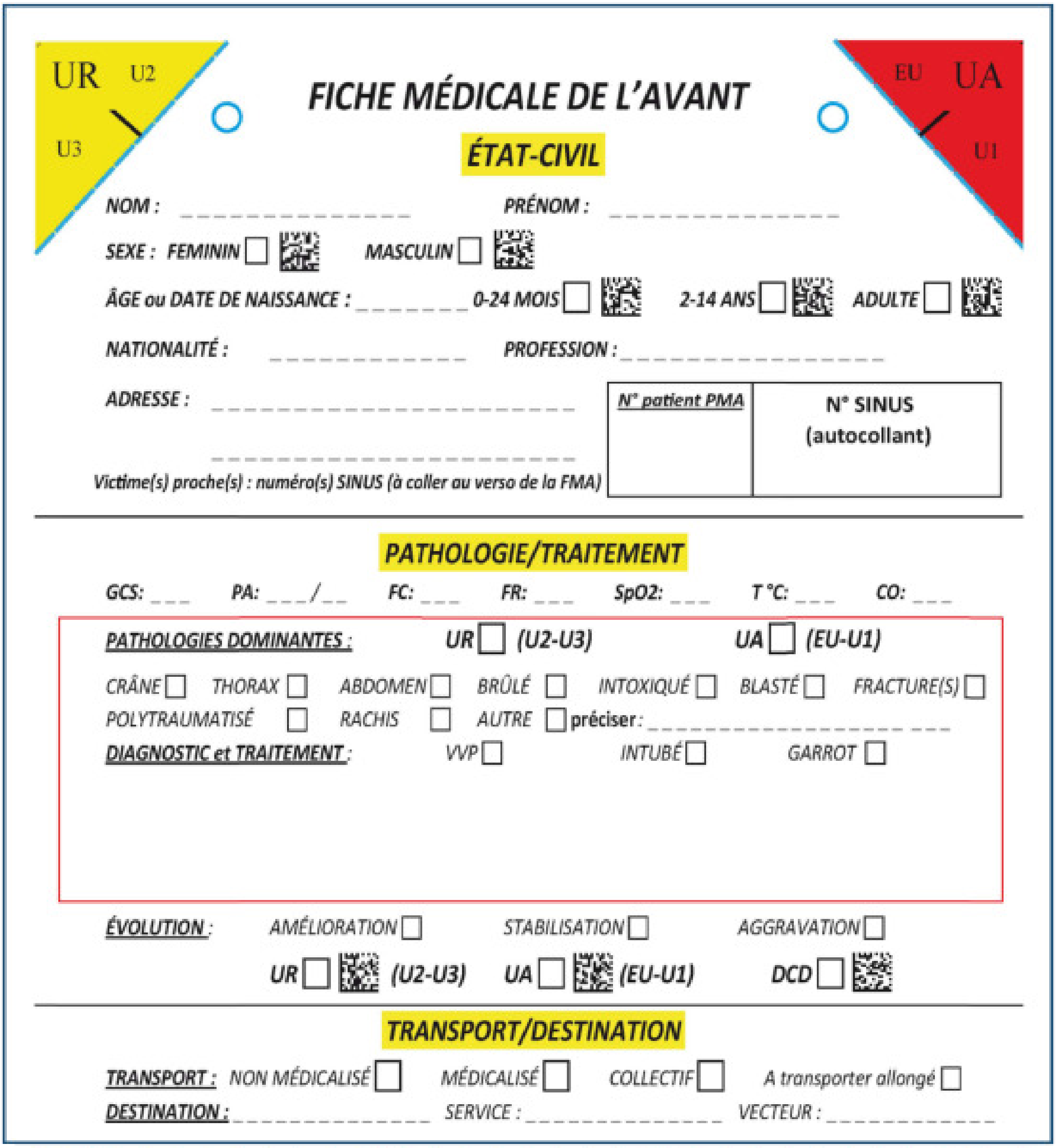
The White plan is used to identify a set of hospitals where the victims can be transported.

It deals with the coordination and the organization of the hospitals' activities in mass causality management. It enables the preparation of the hospitals for the incoming victims regarding the resources' availability such as doctors, nurses, and beds. It consists of a set of procedures that guarantee the resources mobilization. Therefore, each hospital where the White plan is activated must have an exact schedule of their medical staff and a list of available resources.

To manage the mass causality, the national system SINUS ("Système d'Information Numérique Standardisé") is used by the French stakeholders to identify and track victims using a bracelet with a barcode. SINUS is a standardized digital identification system composed of three components. First, an information collect application called "ARCSINUS" enables the input of information and its transmission via a laptop and a barcode scanner. Second, a database allows the real-time centralization of the information so it can be provided to all the involved ERs. Third, an application is dedicated to the strategic level of disaster response to identify the victims and inform their relatives.

SINUS enables the recognition of each victim and the respective disease using a detailed medical record form as shown in Figure 4.2. More specifically, it is used during the triage by the DSM. The DSM fills out the form with information about the victim's identity if it is known (e.g. full name, birth date, sex), their state (UA or UR), their vital signs (heart rate, blood pressure, body temperature), their condition, and the evolution of the victim's state, for instance, if it improved, stabilized, or aggravated. In addition, the DSM specifies the assigned transport mean, and the hospital to which the victim should be transported.

Today, the choice of the most appropriate hospital is made by the DSM according to their expertise, experience, and the number of victims to be evacuated toward not overwhelming the closest hospitals. Consequently, the decision-making process may be negatively affected by the lack of adaptation and visibility considering the variation and the dynamicity of the resources' availability and the unpredictability of the disaster response process. According to the ERs' feedback after the Paris terrorist attacks, the adopted strategies of hospital assignment should be improved [143]. Accordingly, in this study, in order to enhance the process of victims' evacuation, we propose a decision support service to assist the DSM in making better decisions. Our proposal is not to automatize the process and remove the DSM's judgement. Instead, the idea is to support the ERs and expand their capabilities but not to replace them. Specifically, we aim to rank the list of hospitals from the most appropriate to the least appropriate according to the victim's condition, and the final decision is made by the DSM.



UR U2 U3

FICHE MÉDICALE DE L'AVANT

EU UA U1

ÉTAT-CIVIL

NOM : ______________ PRÉNOM : ______________

SEXE : FEMINININ ☐ MASCULIN ☐

ÂGE ou DATE DE NAISSANCE : ________ 0-24 MOIS ☐ 2-14 ANS ☐ ADULTE ☐

NATIONALITÉ : _____________ PROFESSION : __________________

ADRESSE : _________________________

____

Victime(s) proche(s) : numéro(s) SINUS (à coller au verso de la FMA)

N° patient PMA	N° SINUS (autocollant)

PATHOLOGIE/TRAITEMENT

GCS: ___ PA: ___/__ FC: ___ FR: ___ SpO2: ___ T °C: ___ CO: ___

PATHOLOGIES DOMINANTES : UR ☐ (U2-U3) UA ☐ (EU-U1)

CRÂNE ☐ THORAX ☐ ABDOMEN ☐ BRÛLÉ ☐ INTOXIQUÉ ☐ BLASTÉ ☐ FRACTURE(S) ☐

POLYTRAUMATISÉ ☐ RACHIS ☐ AUTRE ☐ préciser : ____________________

DIAGNOSTIC et TRAITEMENT : VVP ☐ INTUBÉ ☐ GARROT ☐

ÉVOLUTION : AMÉLIORATION ☐ STABILISATION ☐ AGGRAVATION ☐

UR ☐ (U2-U3) UA ☐ (EU-U1) DCD ☐

TRANSPORT/DESTINATION

TRANSPORT : NON MÉDICALISÉ ☐ MÉDICALISÉ ☐ COLLECTIF ☐ A transporter allongé ☐

DESTINATION : ______________ SERVICE : ______________ VECTEUR : ____________

Figure 4.2: SINUS: victim's medical record form.

4.3 Related works: Victims' evacuation systems

When disasters strike and engender victims, there is a critical need for an appropriate mass causality management. In the literature, different victim evacuation approaches have been proposed. Most research in this area focuses on two concerns:

1. When will the victim be evacuated? This issue concerns optimizing the allocation of transport vehicles, finding the best evacuation routes, calculating the shortest path, and minimizing the transport time.
2. Where will the victim be evacuated? This issue concerns managing the hospitals' resources availability according to the nature of the victims' injuries.

In this work, our focus is on evacuating the wounded victims to the appropriate hospitals and subsequently improving the allocation of medical resources. Accordingly, the following literature review is concentrated on research that deals with the topic of victims' evacuation during disaster response, considers the healthcare resources availability, and supports the decision-making process of choosing the most appropriate hospitals to transport the victims.

Benssam et al. [60] propose the DEvacuS (Dynamic Evacuation System) framework for dynamic evacuation operations that provides optimal and up-to-date evacuations plans. DEvacuS considers the unpredictability and dynamicity of two changes; the hospitals' occupancy per specialty and the state of the routes for the transport. In fact, the hospital occupancy can be negatively impacted by different factors including the instantaneous unavailability of doctors. In addition, the optimality of the shortest path to the targeted hospitals may be affected by road accidents or bridge destruction. To enhance the evacuation, DEvacuS is composed of the following components: a client device, a request dispatcher, a shortest path calculator, and a resolution system. The system uses the specialty required by the user to search for the list of hospitals that provide this specialty. Then, it calculates the shortest path between the position of the triage site of the victims and the target hospitals. Afterward, the resolution system selects the most appropriate hospital by optimizing the ratio between the shortest path, occupancy, and load balancing among hospitals. However, DEvacuS selects the most appropriate hospital according to the occupancy in a certain specialty service in a hospital. Thus, it considers hospitals' load balancing only in terms of available beds.

Muaafa et al. [144] propose a multi-objective optimization model in order to generate optimal emergency medical response strategies. It concerns the localization of temporary healthcare institutions, dispatching strategies to manage injured victims' evacuation vehicles, and then decide the number of victims to evacuate to each healthcare institution. The aim of the proposed multi-objective optimization model is to minimize the response time and cost of the response strategy.

Nouaouri [145] provides an optimization of the hospitals' human and material resources to enhance the victims' evacuation. However, this work focuses only on the surgeons and their surgical acts scheduling in the operating rooms of hospitals. Various possible disruptions are considered including the overflow of surgical care duration, the evolution of the victim's emergency level, and the insertion of a new victim in the scheduling program.

Dain and Nair [146] present a mixed-integer program that formulates a resource-constrained triage problem called the Severity-Adjusted Victim Evacuation (SAVE) model. This work is concerned with how to effectively evacuate the victims to the different hospitals without overwhelming any single hospital. The SAVE model considers, on one hand, the deterioration condition of the victim's state, the resources availability, and treatment capacity of the hospitals. On the other hand, it considers the ambulances' availability and their capacity to transport the victims. However, concerning the availability of the resource, the SAVE model is focused only on hospital capacity in terms of the number of unoccupied beds.

Engelmann et al. [147] propose an ontology that can be used to support the decision-making process of finding where the hospitalized patients will be allocated. The ontology focuses only on bed availability and it is not evaluated nor used in real scenarios.

Most of these works study the evacuation problem from a single perspective rather than considering the different challenges of the problem. Besides the beds' allocation, the availability of adequate healthcare resources for the victims' needs is of utmost importance. The availability of medical devices and professionals together ensure that victims are properly treated. It is therefore important to consider the victims' needs, the availability of the required resources, and the minimization of the victim's wait time when making the best decision regarding to which hospital victims should be taken.

4.4 Multi-criteria decision-making (MCDM)

Decision-making is the cognitive process of comparing, selecting, or ranking multiple alternatives [148]. In this context, decision-makers have to achieve multiple and usually competing objectives. Multi-criteria Decision-Making (MCDM) is a widely known branch of decision-making. It deals with decision problems under the presence of a set of different criteria to support decision-makers in finding consistent and robust solutions. During the last three decades, MCDM methods have emerged to provide a structured evaluation to decision problems with multiple criteria and to increase the efficiency of the decision-making [149]. These methods aim to assist the decision-making process in order to guarantee the selection of the best solution in accordance with the set of criteria in question [150]. According to [151], the MCDM process comprises the following steps (see Figure 4.3):

1. The intelligence step consists of the determination of the goal of the decision by means of identifying the decision-makers and then clarifying the decision problem.

2. The design step concerns the problem modeling and formulation by defining the set of alternatives and criteria based on the goal of the decision.

3. The choice step consists of selecting the best MCDM method that is suitable for the decision problem.

4. The implementation step concerns the implementation of the method and then the evaluation of the results.

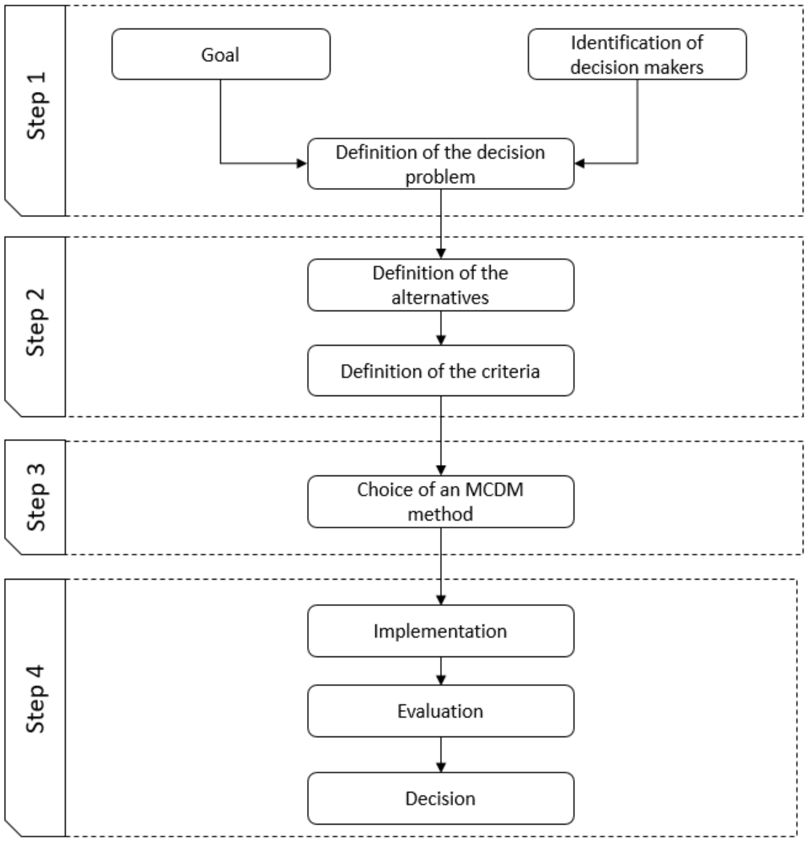


Figure 4.3: The MCDM process.

4.5 Multi-criteria decision-making methods

In the literature, various MCDM methods are proposed to analyze different alternatives according to a set of criteria. The most important and widely used MCDM methods in many application areas are the multi-attribute utility theory (MAUT), the analytical hierarchy process method (AHP), the weighted sum method (WSM), the weighted product method (WPM), the elimination and choice translating reality method (ELECTRE), the technique for order preference by similarity to ideal solutions method (TOPSIS), and the preference ranking organization method for enrichment evaluation (PROMETHEE). These methods vary in complexity and each one has its own strengths and weakness [152].

MAUT is "the more rigorous methodology for how to incorporate risk preferences and uncertainty into multi-criteria decision support methods". It is addressed to compare the utility values of a series of attributes in terms of risk and uncertainty [153].

According to Saaty, AHP is ”a theory of relative measurement on absolute scales of both tangible and intangible criteria based both on the judgment of knowledgeable and expert people and on existing measurements and statistics needed to make a decision” [154]. It is a multiple-attribute decision analysis technique designed for complex systems that involve various conflicting criteria and alternatives. It uses a paired wise comparison to judge the weight. AHP is widely employed because of its ability to check the consistency of the proposed approach.

WSM is widely used for single-dimensional problems. It defines the optimal alternative that represents the best value of the weighted sum. It is a method in which all criteria should be all ”benefit-type” or ”cost-type” so that it can be applied correctly. WPM is similar to WSM. The main difference is that weighted parameters are multiplied instead of summed. The different alternatives are compared by multiplying the number of ratios, one for each criterion [155].

ELECTRE is a family of outranking methods consisting of seven different models (I, II, III, IV, A, IS and TRI) derived from the original ELECTRE I. These latter perform an outranking of a set of alternatives by determining their concordance and discordance indexes [156]. ELECTRE employs an indirect method that ranks alternatives by means of pairwise comparison. It concentrates on the analysis of the dominance relations that exist among the alternatives. Due to its complex computational procedure, it is a time-consuming method in the absence of a dedicated software implementation.

TOPSIS is developed by Huang and Yoon as an alternative to ELECTRE. It is based on the idea that the best alternative is the one that is closest to its positive-ideal solution and farthest from the negative-ideal solution [157]. The positive-ideal solution maximizes the benefit criteria and minimizes the cost criteria, whereas the negative-ideal solution maximizes the cost criteria and minimizes the benefit criteria [158].

PROMETHEE uses the outranking principle to rank the alternatives. It carries out a pairwise comparison of alternatives in order to rank them. It is based on positive and negative preference flows for each alternative that are used to rank them according to the defined weights [159].

To use an MCDM method, the type of the decision problem should be identified. In fact, there are four main types of analysis that can be performed:

- The choice problem is to select a single best option or a limited set of alternatives.
- The sorting problem is to classify the set of alternatives into a predefined homogeneous group called categories.
- The ranking problem is to order the set of alternatives from the best to the worst according to scores or pairwise comparison.
- The description problem is to identify the major distinctions between the different alternatives and their consequences.

Table 4.1 presents the main strengths and limitations of the presented methods and the decision problem they solve. In the literature, researchers have attempted to use hybrid methods by combining different MCDM methods in order to compensate for the limitations and make use of the strength of both methods [158].

Table 4.1: A comparative study of the commonly used MCDA methods.

Method	Strengths	Limitations	Decision problem
MAUT	• Considers the uncertainty. • Considers the preferences.	• Requires a large number of inputs.	• Choice • Ranking
AHP	• Scores the model. • Reduces the complexity of decision-making. • Easy to use and to understand. • Does not involve complex mathematics. • Based on a hierarchical structure and thus each criterion can be better focused and transparent. • Based on a semantic scale to express the decision-maker preferences. • Does not need a large amount of data. • Enable consistency check.	• The involvement of more decision-makers can make the problem more complicated while assigning weights. • Instability of the ranking result in case of a large number of alternatives. • Variation of the alternatives' raking following the removal or addition of one or more alternatives.	• Choice • Ranking

WSM	• Homogeneity of the criteria. • Simple computation. • Suitable for single dimension problem.	• Fails to integrate multiple preferences. • Not suitable for problems that involve very different types of criteria.	• Choice
WPM	• Homogeneity of the criteria.	• Assigns null values to impossible criteria.	• Choice
ELECTRE	• Deals with both quantitative and qualitative features of criteria. • Final results are validated with reasons. • Deals with heterogeneous scales.	• Demands a good understanding of one's objectives especially when dealing with quantitative features. • Time-consuming.	• Choice: ELECTRE I • Ranking: ELECTRE III • Sorting: ELECTRE-Tri
TOPSIS	• Works with fundamental ranking. • Makes full use of allocated information. • The information do not need to be independent.	• Arbitrary choice of the distance between the ideal solution point and the negative ideal solution point.	• Choice • Ranking
PROMETHE	• Incorporate uncertain and fuzzy information.	• Does not structure the objectives properly. • Complicated.	• Choice • Ranking

4.6 Towards the selection of an MCDM method

To choose an appropriate MCDM method for the victims' evacuation decision-making, we followed a set of guidelines proposed by Guitouni, et al. [160].

Guideline G1 is to determine the stakeholders of the decision process and if there is a need to use a group decision-making method. In our context, the healthcare unit members, and more specifically the DSM, is responsible for the victims' evacuation process. He ensures the triage of wounded victims, he is responsible for identifying the disease of each victim, and then choosing the most appropriate hospital where this latter should be transported. Accordingly, we do not have to consider the use of group decision-making methods.

Guideline G2 is to consider the decision-making cognition to compare the different alternatives including pairwise comparison, utility and value function, distance to the ideal point approach, etc. The pairwise comparisons meet most our requirements because it is very similar to the human way of thinking. It involves comparing pairs of criteria by asking how much important one criteria is than the other according to a predefined scale. We think that it is much easy and efficient to compare only two elements at a time. Furthermore, pairwise comparisons are recommended when it is not possible to define a utility function that is complex and time-consuming [161].

Guideline G3 is to define the decision problem that the MCDM method should solve. In disaster response, the decision-making process is even more complex and delicate, since it requires not only the reflection of economic or technical issues but also the consideration of the human factor and how to maximally saving lives. In our context, the ERs are looking for the most appropriate hospital that provides the required medical resources according to the victims' needs. In the beginning, we thought that we need to choose the single best hospital from the set of alternatives. But after further reflection, raking the different hospitals from the most appropriate to the less appropriate is more advantageous. In fact, responding to a disaster is a highly complex and time-constrained situation; in case ERs figure out that they cannot reach the first hospital because of a roadblock, they can immediately choose the second hospital without wasting time by ruing the system one more time. Moreover, the aim of this study is to support the DSM in his decision-making and not substitute his role. Accordingly, it is more reliable to propose a list of ranked hospitals from the most appropriate to the less appropriate according to the victim's disease, and the final decision is made by the DSM. Therefore, since we need to get an alternatives' ranking, a ranking method is appropriate. The MCDM methods that provide alternatives' ranking are MAUT, AHP, ELECTRE III, PROMETHE, and TOPSIS. In accordance with the G2, only AHP adopts a pairwise comparison.

According to various review studies in the literature [161] [158] [152], it is observed that AHP is the most commonly applied MCDM tool in various research fields due to its simplicity, flexibility, straightforwardness, and comprehensibility. Kabir et al. [158] noticed that the percentage of AHP papers increased from about 22% in 2004 - 2006 to over 45% in 2007 - 2009 and 44% in 2010 – 2012; "AHP has dominated as single MCDM method ever since". In fact, AHP is able to reduce the complexity of decision-making in a reliable way [162]. Thus, it makes complex problems simpler so that a decision can be made. Moreover, it provides an easily understandable approach for practitioners. Furthermore, one of the major advantages of AHP is that the consistency index is calculated. The aim is to ensure that the judgments are consistent and the final decision is well-made.

Regarding the identified limits of AHP, in the proposed work, the set of alternatives are fixed by the white plan from the beginning of the disaster response process. Moreover, the number of activated hospitals is not a large number that can unstable the ranking result or slow down the processing time.

4.7 Analytic Hierarchy Process (AHP)

To use the AHP method and to obtain the ranking of the different alternatives, the following steps should be considered (see Figure 4.4).

Step one: Problem structuring

The problem structuring step consists of the decomposition of the complex problem into a hierarchy where the top element is the goal of the decision, the mid-level represents the criteria, and the lowest level represents the different alternatives.

Step two: Priority calculation

The priority calculation step determines the priority of the criteria in the decision. It consists of establishing an n×n square matrix $A = [a_{ij}]_{nn}$ of pairwise comparison between the different criteria with respect to the goal stated at the top hierarchy. Hence, criteria are compared in pairs to identify their relative preference. The use of pairwise comparison is mainly evaluated on the fundamental of one to nine scale (see Table 4.2). The increasing numerical values indicate the increasing importance of criteria.

$$A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{pmatrix} \tag{4.1}$$

Table 4.2: The one to nine fundamental scale.

Degree of importance	Definition
1	Equally important
2	Weak
3	Moderately important
4	Moderate plus
5	Strongly important
6	Strong plus
7	Very strong importance
8	Very, very strong importance
9	Extremely important

Step three: Normalization

Every element a_{ij} of the matrix A is normalized by dividing each element in a column by the sum of the elements in the same column in order to create a normalized pairwise comparison matrix A'. The normalization is done using the following equation:

$$a_{ij}^{'} = \frac{a_{ij}}{\sum\limits_{i=1}^{n} a_{ij}} \tag{4.2}$$

Step four: Priority vector calculation

The priority vector (eigenvector) w is computed by dividing the total sum of elements in each row of matrix A' by the number of the matrix dimension n. w is calculated using the following equation:

$$w_i = \frac{\sum\limits_{i=1}^{n} a_{ij}^{'}}{n} \tag{4.3}$$

Step five: Consistency check

The consistency check is performed to detect possible contradictions in the entries. In the AHP method, the maximum eigenvalue (λ_{max}) is a significant parameter of the consistency validation. It is calculated from the consistency value CV using the following equation:

$$CV_i = \frac{\sum\limits_{j=1}^{n} a_{ij} w_j}{w_j} \tag{4.4}$$

$$\lambda_{\max} = \frac{\sum\limits_{j=1}^{n} CV_i}{n} \tag{4.5}$$

λ_{max} is used to calculate the consistency index (CI) as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4.6}$$

Then, the consistency ratio (CR) is calculated basing on the CI and the random consistency index value (RI) (see Table 4.3). The CR should not exceed 0.1 so that the matrix can be considered as having an acceptable consistency.

$$CR = \frac{CI}{RI} \leq 0.10 \quad (4.7)$$

Table 4.3: Random consistency index value (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Step six: Alternatives weights

If the CR is acceptable, the eigenvector of each criterion is multiplied with all alternatives and the total sum of each alternative is calculated.

Step seven: Alternatives ranking

The final step is to compare the total sum of each alternative and carry out the ranking.

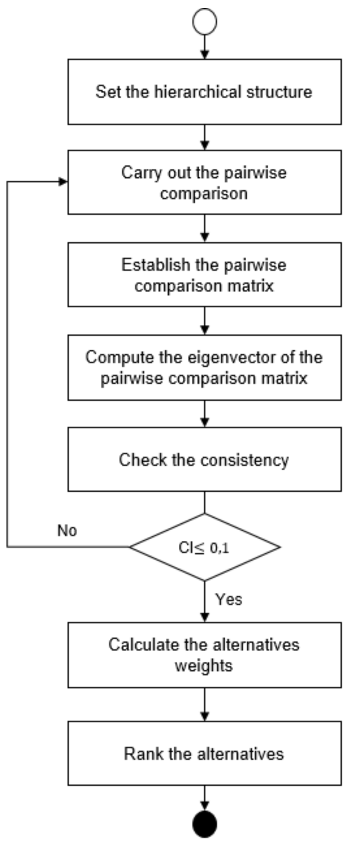


Figure 4.4: AHP steps.

4.8 Ontology-driven multi-criteria decision support service: PROOVES

To improve the victims' evacuation process, we propose a multi-criteria decision support service called PROOVES for "POLARISC Ontology-Based Operational Victims Evacuation Service". It is responsible for finding to which one of several hospitals should each victim be transported? The main purpose of PROOVES is that the victims will be transported to the most appropriate hospitals where they can receive as soon as possible an adequate medical care according to their medical needs. The hospital selection depends on the transfer time to reach the hospital, the availability of the needed medical resources, and the victims' wait time to receive the medical care. The architecture of PROOVES is presented in Figure 4.5.

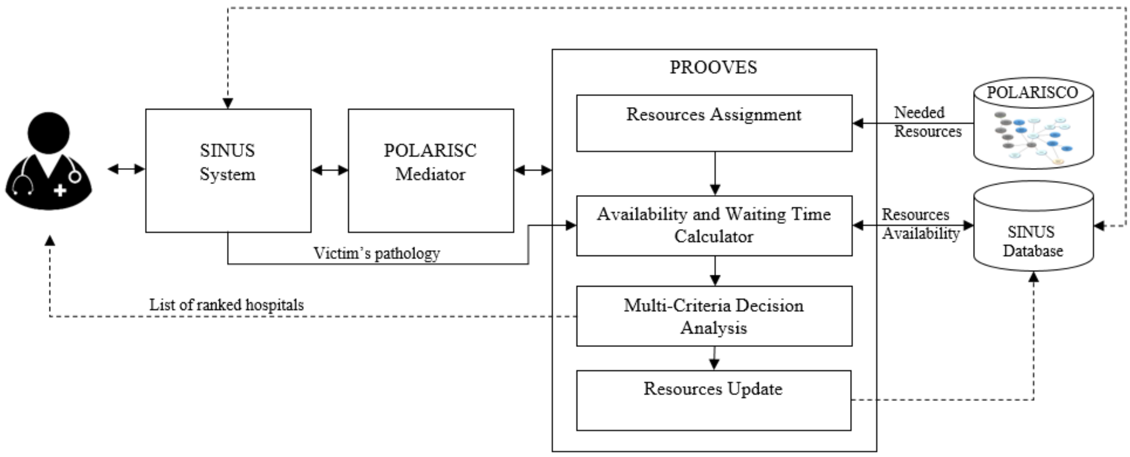


Figure 4.5: PROOVES architecture.

To find where to transport a victim, the DSM responsible for the evacuation team fill the victim's medical record in the SINUS system and submits the request of searching the most appropriate hospital from the list of activated hospitals by the White plan. To do so, POLARISC mediator receives the request and then interrogates PROOVES to perform the multi-criteria decision analysis. PROOVES first algorithm is divided into three steps; resource assignment, availability and wait time calculator, and multi-criteria decision analysis. First, the resources assignment step enables the determination of the needed medical resources and the required staff according to the victim's disease. To do so, the victims' evacuation module of POLARISCO is queried and subsequently, a list of specialized staff and medical equipment is returned in accordance with the disease included in the user request.

Second, the list of activated hospitals is got from SINUS database and so as their initial resources and transfer time. The following computation is done for each activated hospital. The arrival time is computed based on the transfer time between the disaster site and the target hospital. Then, the system checks the availability of the different needed resources. If a resource is available, the system calculates the victim's wait time. The availability and wait time calculator is a preprocessing step that prepares the information required to perform the third step, the multi-criteria decision analysis. In the third step, the list of hospitals is ranked using the AHP method from the most appropriate to the less appropriate according to their transfer time, resources' availability, and the victim's wait time. Finally, the ranked list will be transmitted to the DSM who will make the final decision. Once a hospital is selected, the resource wait time is updated, by a second algorithm, so that it can be considered for the next process. Figure 4.6 summarizes the process of the proposed system.

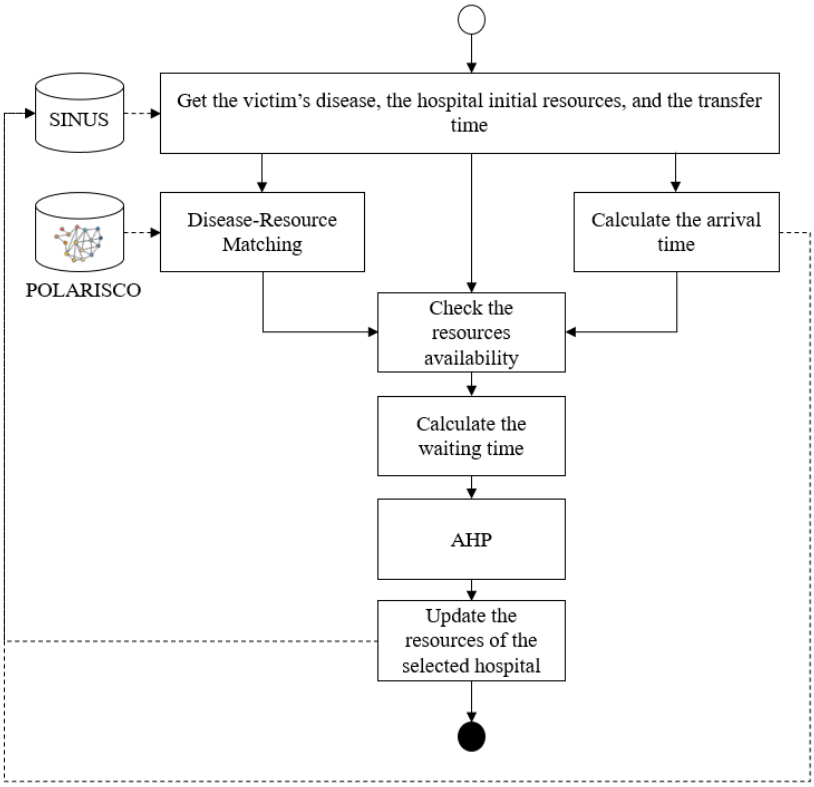


Figure 4.6: PROOVES process.

4.8.1 The healthcare resources module of POLARISCO

In the following, more details about the healthcare resources ontological module of POLARISCO are presented. On the one hand, it formalizes the different healthcare resources including hospitals' staff and equipment. On the other hand, it categorizes the different possible diseases and associates them to the healthcare resources that are required to deal with such a case. Moreover, it defines the victims' evacuation process and the different participants. To do so, we reused the PCC module and the healthcare unit module of POLARISCO.

We started by defining what is a disease. Since we use BFO as an upper-level ontology and CCO as mid-level ontologies, we followed its definition of disease. According to [163], a disease is "a disposition to undergo pathological processes that exists in an organism because of one or more disorders in that organism". Accordingly, "cco: disease" is defined by the agent module of CCO as a subclass of ”bfo: disposition”.

Afterward, to design the ontological module, we tried to reuse existing ontologies as much as possible to reduce the modeling complexity and to maximize future data integration. Therefore, we referred to existing biomedical ontologies within the OBO Foundry [164] due to their quality, considerable usage, common design principles, and compliance with BFO.

We reused the Disease Ontology (DO) that provides a standard representation and unified classification of human disease types. DO is an open-source ontology that was developed initially in 2003 by the genetic medicine center of Northwestern University as part of the NUgene project [165]. It provides a clear definition of each disease in order to unify the representation of disease among various terminologies and vocabularies and to enable their consistent use and application in the biomedical field. The DO semantically captures disease terms across different vocabularies such as MeSH, NCI's thesaurus, ICD, SNOMED CT, and OMIM disease-specific. In the literature, a variety of vocabularies have been developed in order to standardize biomedical terms including disease. However, unlike DO, none of them are classified around the term disease. Furthermore, DO adopt the BFO definition of a disease as a realizable disposition.

In DO, diseases are organized into eight main nodes; disease by anatomical entity (e.g. cardiovascular system disease), disease of metabolism, physical disorder, syndrome (e.g. Wolfram syndrome), genetic disease, disease of cellular proliferation (e.g. cancer), disease by infectious agent (e.g. anthrax), and disease of mental health. Syndromes are defined as ”a disease characterized by a group of signs and symptoms that occur together and characterize a particular abnormality”. In POLARISCO, we reused DO's categorization of diseases as shown in Figure 4.7 and then we populate the ontology reusing only diseases that are considered as an absolute emergency.

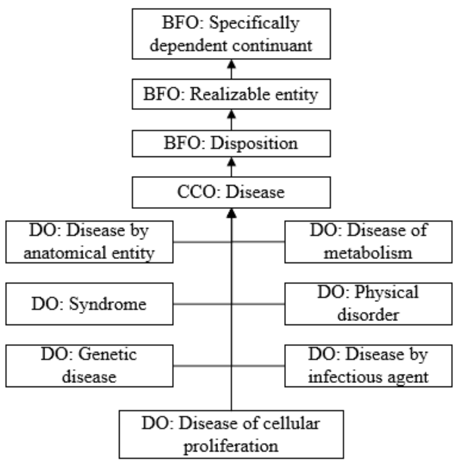


Figure 4.7: Classification of diseases in POLARISCO.

To represent the healthcare resources, we started by reusing classes from the eagle-i resource ontology (ERO) [166]. ERO was developed by a consortium of nine universities with a grant from the National Institutes of Health (NIH). ERO is a modular set of ontologies that uses BFO as an upper-level ontology and reuses the Resource Ontology (BRO) [167] in order to represent biomedical research resources such as organisms, instruments, software, biological specimens, human studies, and research opportunities.

In fact, we reused only classes from the instruments module to define the medical equipment that can be available in the hospitals. In ERO, "ero: instrument" is a subclass of "bfo: material entity". In POLARISCO, we used a "medical device" as a "bfo: material entity" to represent all the types of resources. It is defined as "An article, instrument, apparatus or machine that is used in the prevention, diagnosis or treatment of illness or disease, or for detecting, measuring, restoring, correcting or modifying the structure or function of the body for some health purpose" [168]. We can notice that the medical device term englobes the definition of an instrument. Then, we defined three types of medical devices. First, the "diagnostic device" is any type of equipment or tool used in a hospital for diagnosing a patient's condition (e.g. medical imaging machine, pulse oximetry). Second, "treatment device" is any device used to provide therapeutic benefit for a certain disease and to restore the function of the affected organs or tissues within a body (e.g. surgical machines, infusion pumps, medical lasers). Third, a "life support device" is any device that aims to maintain the bodily function of a patient (e.g. dialysis machine, incubators). We reused the classes of ERO under "medical device" and following the three identified categories as shown in Figure 4.8. Concerning the medical staff, the different specialties are already defined as roles in the healthcare units module of POLARISCO as depicted in Figure 4.9.

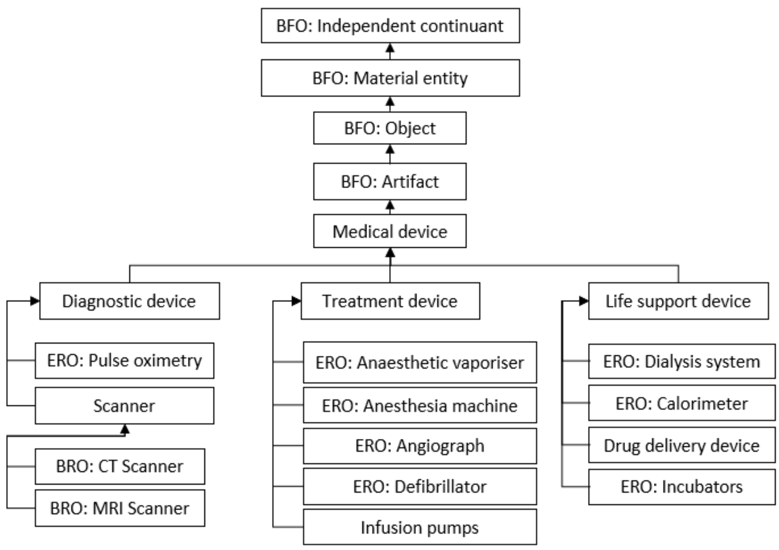


Figure 4.8: Classification of medical devices in POLARISCO.

To match diseases and the required resources, we defined an act of treatment as a subclass of "cco: act". An act of treatment is subdivided into different types; act of nursing, act surgery, etc. Then, we defined the relationship "needs" to associate each disease to the required act of treatment. Afterward, each act of treatment is realized by a specific healthcare unit role and involves a specific medical device. In fact, an act of treatment is the go-between

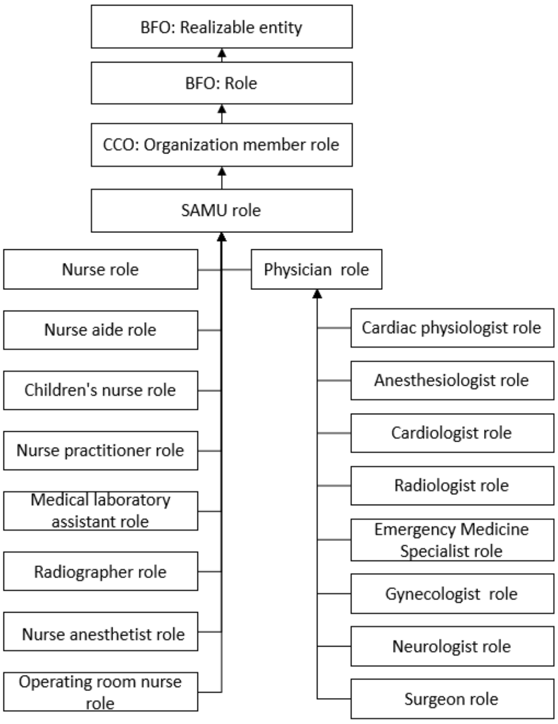


Figure 4.9: Classification of medical staff in POLARISCO.

diseases and resources. For instance, an act of cardiovascular surgery is realized by a cardio-thoracic surgeon and involves an operating room. In fact, a medical device cannot be used without the intervention of specific staff. It requires a human resource to carry some specific actions. Accordingly, we linked every act of treatment to a couple of medical devices and their associated staff. For instance, to diagnosis a heart disease, the physician needs a cardiac computerized tomography (CT) scan. To perform this latter, both the CT scanner and the radiographer should be available. To highlight the correlation between disease and medical resources, Figure 4.10 demonstrates an example of the required resources for cardiomyopathy surgery. To realize an act of surgery, in terms of specialist physicians, a cardio-thoracic surgeon and an anesthesiologist are essential. Concerning the assistant staff, an operating room nurse and a nurse anesthetist are needed. The operating room must be equipped with a defibrillator, anesthesia machines and so on. Each one of these medical devices needs human intervention. For example, the anesthetic vaporizer is used by a nurse anesthetist.

In fact, in the healthcare resources ontological module of POLARISCO, we defined only the essential medical devices and specialized staff for each disease that should be available to efficiently treat the victims' disease and that cannot be substituted. Thus, the resource management is adapted to the context of disaster response.

To effectively manage the resource allocation demands over time and to calculate the wait time to receive the required care, we designate an average non-availability duration per act of treatment and subsequently per resource and staff. Hence, we define a resource utilization

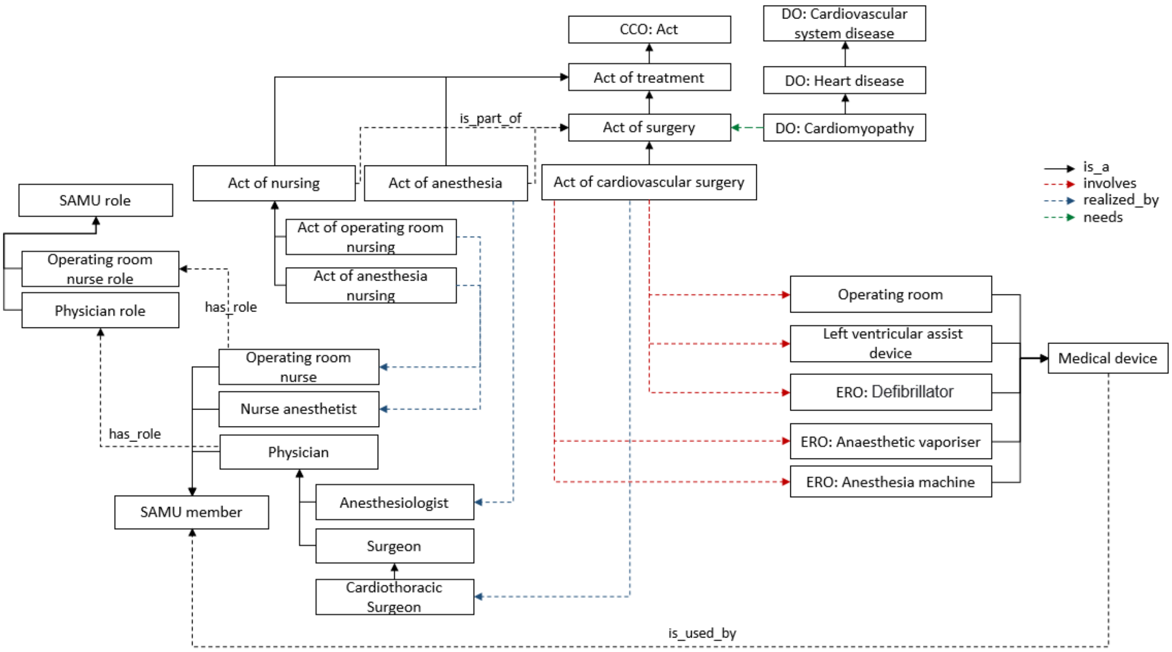


Figure 4.10: Example of the association of healthcare resources to diseases in POLARISCO.

metric that expresses how long a resource is needed to accomplish a certain task. This enables us to answer the question: how many minutes an act of treatment last? To do this, we used the time module of CCO to represent temporal intervals. Then, to relate each act of treatment to its temporal interval, we defined the relationships ”has_average_duration”. For instance, an act of scanning takes thirty minutes (see Figure 4.11). Since an act of scanning is realized by a radiographer and involves a scanner, we can conclude that the non-availability duration of a scanner and a radiographer are also thirty minutes.

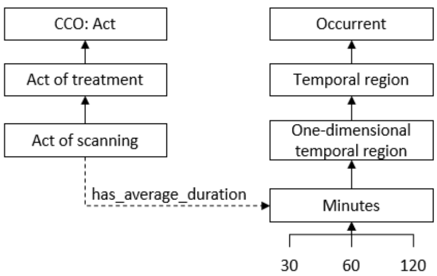


Figure 4.11: Example of resource duration of use.

In the following, we highlight the interaction between the different classes of PCC, healthcare units, and healthcare resources modules. Figure 4.12 shows a partial view of the ontology. Since both firefighters and healthcare units ensure the evacuation of victims, an act of evacuation is defined as a subclass of ”cco: act” in PCC. An act of evacuation is ordered by a DSM who choose the hospital destination and realized by an evacuation agent who transport the victim to the hospital using a specific transport mean (e.g. ambulance). The DSM is a SAMU member affiliated to SAMU and has role "DSM role". The different SAMU members are agent in "pcc: hospital". Then, in an act of evacuation, a victim is transported to a hospital. Both "victim" and "hospital" are already defined in PCC as subclasses of "bfo: person" and "cco: artifact", respectively. Moreover, every medical device is used by a staff and located in a specific hospital.

To summarize, the resulting healthcare resources ontological module of POLARISCO is a combination of classes already existing from biomedical ontologies (DO and ERO), classes from PCC and healthcare units module, and classes we specifically created in this module in order to assign for each disease the needed healthcare resources.

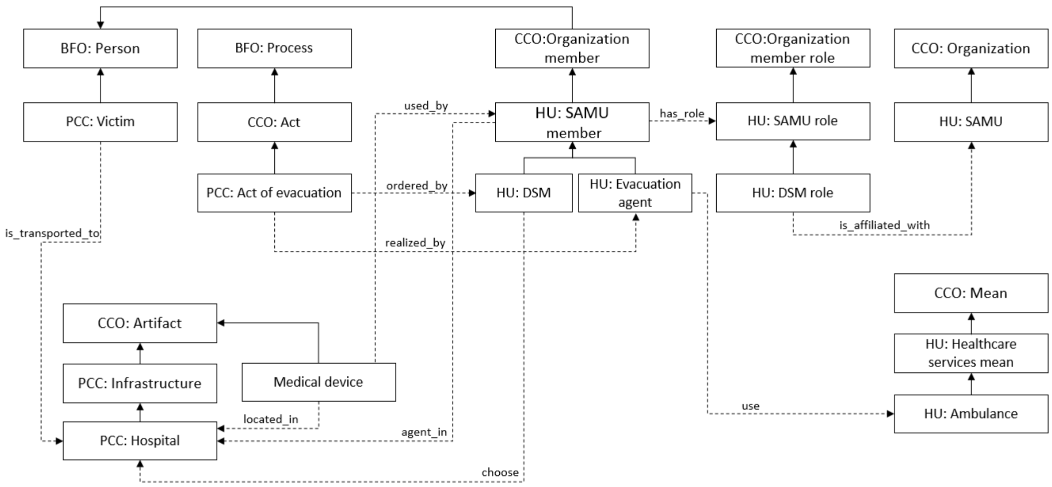


Figure 4.12: Interaction between PCC, healthcare units, and healthcare resources modules.

4.8.2 Formalism and definitions

In this subsection, we present a formal definition of the annotations that will be used when elaborating the proposed algorithms.

V is the set of victims to be evacuated where $V = \{v_1, v_2 \ldots v_n\}$.

H is the set of activated hospitals by the White plan where $H = \{h_1, h_2 \ldots h_n\}$.

We consider that the triage site is the starting point to query the system for available hospitals to transport the victims.

We consider that the capacity of each transport mean is one victim and victims are evacuated one by one.

We assume that there is an available transport mean to transfer v_i to h_i.

t_{h_i} is the transfer time needed to transport the victim v from the triage site to the targeted hospital h_i.

We consider that the transfer time t_{h_i} is a static variable already known and retrieved from the SINUS database.

$t_{arrival}$ is the arrival time to the hospital that considers the transfer time t_h.

R_{h_i} is the set of initial resources of a hospital h_i.

D is a set of diseases where $D = \{d_1, d_2 \dots d_n\}$ and d_i is the disease of a victim v_i. If a victim has different diseases, the DSM inputs only the most urgent one.

R_{needed} is the set of the needed resources for a disease d where:

- $R_{needed}(d) = \{(m_1, s_1), (m_2, s_2) \dots (m_n, s_n)\}$
- (m_i, s_i) is the couple of medical device and staff that should be available at the same time in a hospital h_i for a disease d_i where:
  - $m_i \in M = \{m_1, m_2 \dots m_n\}$.
  - $s_i \in S = \{s_1, s_2 \dots s_n\}$.

$t_{duration}$ is the average non-availability duration of a material m or a staff s.

t is the time period index.

WT_h is the set of wait time of the couples of needed resources in a hospital h where $WT_h = \{wt_{h_1}, wt_{h_2} \dots wt_{h_n}\}$.

Max_{wt_h} is the wait time in a hospital h

A_h is the total of needed resources available in a hospital h.

RH is the list of ranked hospitals such that $RH \subseteq H$.

4.8.3 The victims' evacuation algorithms

When the disease of the victim is inputted in the SINUS system and the search of the most appropriate hospital is launched, PROOVES proceeds to compute the availability and wait time of the resources in order to produce the needed data to perform the multi-criteria decision analysis. This step is done using the first algorithm "Hospitals' ranking".

To start, the algorithm requires as input the victim's disease and the list of the activated hospitals by the White plan and their respective initial resources and transfer time which may be retrieved from SINUS database. Then, it searches for the needed resources as a set of couples of materials and staff by querying POLARISCO. Afterward, it checks if the couples of these resources are available or not for each hospital by examining its list of initial resources.

If a couple of resources is available, the number of available resources in this hospital is incremented and the algorithm computes the victim's wait time to use these latter. Hence, the wait time is calculated basing on the difference between the average non-availability duration of each resource and the arrival time of the victim to the hospital. In fact, the system looks for the resource that has a minimum of wait time. For instance, a couple of a surgeon and an operating room is needed, knowing there are three operating rooms and four surgeons in the hospital. First, the system will choose the surgeon and the operating room with a minimum wait time. Second, it will select the maximum wait time of the two of them because one resource cannot be used without the other. Then, we consider the wait time of the previous victim that is using the same resource; if the wait time ti is less than t_{i-1} than t_i will be the sum of ti-1 and the duration of non-availability $t_{duration}$. Afterward, the transfer time is deducted from the wait time. Once the algorithm computes the wait time of all available resources, the maximum value is selected.

The transfer time, the availability, and the maximum wait time are the input parameters of the AHP method. Once the AHP method is applied, the output result of this algorithm consists of a ranked list of hospitals. This list is displayed to the DSM so that he could make the final choice. The pseudo-code of "Hospitals' ranking" algorithm is provided in Algorithm 2. Once he selects the hospital where the victim will be evacuated, the system updates the wait time of the resources that will be used to treat the victim using the second algorithm "Hospitals' update". The pseudo-code of the second algorithm is provided in Algorithm 3.

To summarize, the two algorithms are mainly about 5 steps as shown in Figure 4.13:

1. Get the victim's disease.

2. Query the needed resources of the identified disease from POLARISCO.

3. Get the hospitals' resources.

4. Check the resources' availability in each hospital.

5. Get the transfer time.

6. Calculate the wait time to use a couple of resources.

7. Rank the hospitals using AHP.

8. Update the resources of the selected hospital.

Algorithm 2 Hospitals' ranking

Input :
$V = \{v_1, v_2, v_3 \ldots v_n\}$: Set of victims to be evacuated
$H = \{h_1, h_2, h_3 \ldots h_n\}$: Set of activated hospital
R_{h_i} : Set of initial resources of a hospital h_i
d: Victim's disease
t_{h_i} : Transfer time to a hospital h_i
$POLARISCO$: The global ontology
Output :
RH: List of ranked hospitals
Variables :
$R_{needed}= \{(m_1,s_1),(m_2,s_2) \ldots (m_n,s_n)\}$: set of the needed resources for a v_i including Staff s and Materials m
A_h: Number of needed resources available in h
$t_{duration}$: Average non-availability duration of a resource
$WT_h= \{wt_{h_1}, wt_{h_2}, wt_{h_3} \ldots wt_{h_n}\}$: set of resources' Wait time in h_i
Sum_{wt_h}: Sum of the wait time of the needed resources
AVG_{wt_h}: Average wait time of all the needed resources in h_i
$t_{arrival}$: Arrival time of the victim to the hospital
t: Time period index

```
begin
    Initialize a list R_needed ⟵ {}
    Initialize a list WT_h ⟵ {}
    A_h = null
    t_{M_h} = null
    t_{S_h} = null
    foreach v ∈ Victims do
        d ⟵ getDisease(v)
        R_needed ⟵ getResources(d, POLARISCO)
        foreach h ∈ H do
            t_h ⟵ getTransferTime(h)
            t_arrival ⟵ t + t_h
            R_h ⟵ getInitialRessources(h)
            foreach (m_i, s_i) ∈ R_needed do
                if (m_i ∈ R_h)&&(s_i ∈ R_h) then
                    A_h ⟵ A_h + 1
                    M_a ⟵ getAvailableMaterial(h)
                    S_a ⟵ getAvailableStaff(h)
                    t_i ⟵ max{min(t_j|j ∈ M_a), min(t_j|j ∈ S_a)}
                    if t_i < (t_{i-1} + t_duration) then
                        t_i ⟵ t_{i-1} + t_duration
                    wt_h ⟵ t_i − t_arrival(v)
                    WT_h ⟵ push(wt_h)
            Max_{wt_h} ⟵ max(WT_h)
        RH ⟵ AHP(t_h, A_h, Max_{wt_h})
        return (RH)
```

Algorithm 3 Hospitals' update

Input :

$SelectedHospital$ = The hospital selected by the DSM from the list of ranked hospitals RH

$H = \{h_1, h_2, h_3 \ldots h_n\}$: Set of activated hospital

R_{h_i} : Set of initial resources of a hospital h_i

Variables :

R_{needed}= $\{(m_1,s_1),(m_2,s_2) \ldots (m_n,s_n)\}$: set of the needed resources for a v_i including Staff s and Materials m

$t_{duration}$: Average non-availability duration of a resource

t: Time period index

begin

find $SelectedHospital$ in H

foreach $(m_i, s_i) \in R_{needed}$ **do**

$M_a \longleftarrow getMaterial(SelectedHospital)$

$S_a \longleftarrow getStaff(SelectedHospital)$

$M_{min} \longleftarrow min(t_i/i \in M_a)$

$t_{M_{min}} \longleftarrow t_{M_{min}} + t_i$

$S_{min} \longleftarrow min(t_i/i \in S_a)$

$t_{S_{min}} \longleftarrow t_{S_{min}} + t_i$

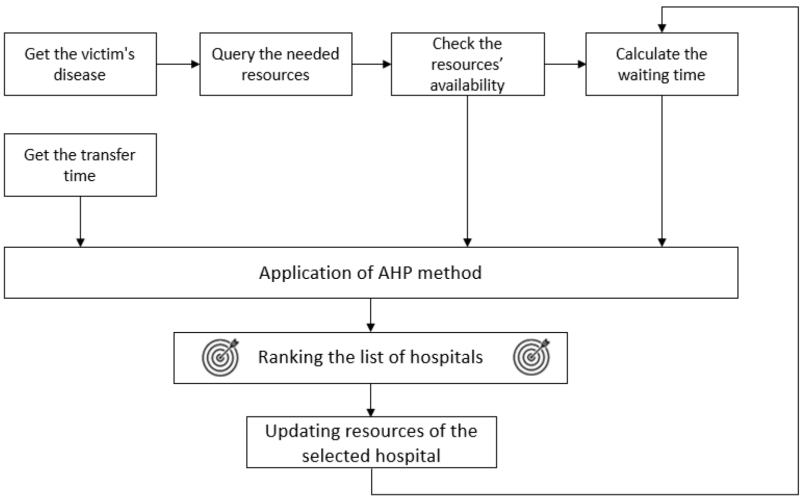


Figure 4.13: The different steps of PROOVES algorithm

4.9 Implementation and use-case evaluation and validation

In this section, we will address how well the PROOVES service does using a case study according to the following three steps; the pairwise comparison and consistency check, the

AHP inputs computing, and the alternatives ranking. It should be noted that the first step is applied just once because the criteria weights are fixed by the emergency experts from the start. Once the consistency is checked and validated, the system can be used. Each time there is a victim to evacuate, the AHP inputs are computed and then the alternatives are analyzed and ranked.

4.9.1 Pairwise comparisons and consistency check

The AHP method will be applied to rank the different hospitals from the most appropriate to the less appropriate. The considered methodology involves different steps as presented in section seven.

Step one: Problem structuring

The addressed problem is structured into a hierarchy model as depicted in Figure 4.14. Level one represents the goal, level two represents the different criteria, followed by the alternatives in the third level.

- Goal: which is the most appropriate hospital to transport the victim?
- Criteria: the hospitals ranking depends mainly on three criteria:
  - The transfer time (c1).
  - The resources' availability (c2).
  - The wait time to receive medical care (c3).
- Alternatives: the possible alternatives are the list of Paris hospitals activated by the White plan when responding to the November 13, 2015, terrorist attacks.

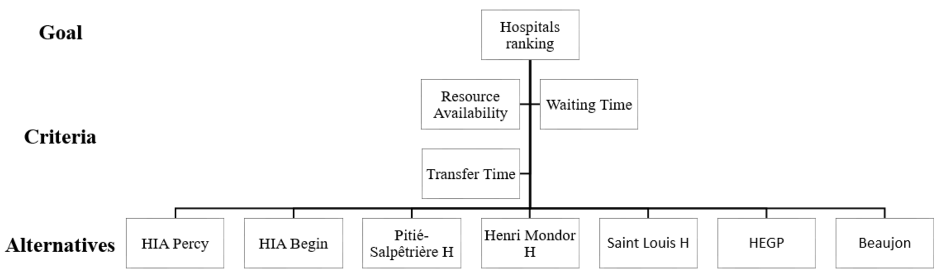


Figure 4.14: The proposed hierarchy model.

Step two: Priority calculation

Each criterion is evaluated compared to the others based on Saaty one to nine scale (see Table 4.4). Accordingly, the pairwise comparison matrix A is constructed. The values of the following pairwise comparison are made by emergency experts and more specifically by the

Table 4.4: Pairwise comparison of the different criteria.

	Transfer time	Resources availability	Wait time
Transfer time	1	1/7	1/5
Availability	7	1	3
Wait time	5	1/3	1

DSM. Specifically, the availability and the wait time are more important than the transfer time. The availability is more important than the wait time.

$$A = \begin{pmatrix} 1 & 0.142 & 0.2 \\ 7 & 1 & 3 \\ 5 & 0.333 & 1 \end{pmatrix} \tag{4.8}$$

Step three: Normalization

In order to obtain the weight of each criterion, the sum of each column is calculated (see Table 4.5). Then, the normalization of the pairwise comparison matrix is performed by dividing the content of each cell by the sum of its column.

Table 4.5: Normalization of the pairwise comparison matrix A.

	Transfer time	Resources availability	Wait time
Transfer time	0.077	0.096	0.0476
Availability	0.538	0.678	0.714
Wait time	0.384	0.225	0.238

Step four: Priority vector calculation

The weight of the different criteria is computed using the priority victor by calculating the average of the rows (see Table 4.6). We can observe from the criteria weight rank that the mentioned preferences are respected.

Table 4.6: Calculation of the priority vector w.

	Transfer time	Resources availability	Wait time	w	Rank
Transfer time	0.077	0.096	0.0476	0.073	3
Availability	0.538	0.678	0.714	0.643	1
Wait time	0.384	0.225	0.238	0.282	2

Step five: Consistency check

Before proceeding to the alternatives analysis step, it is essential to make sure that the criteria weights make sense and there is no absurd contradiction in the pairwise comparison. Accordingly, this step is very important to checks the system consistency by calculating the consistency index (CI) and the consistency ratio (CR). It is regarded as one of the most advantageous features of the AHP. To do so, we start by calculating the weight sum vector Aw and the average consistency vector λ_{max}. Then, the CI is determined where n is the number of criteria.

$$Aw = \begin{pmatrix} 1 & 0.142 & 0.2 \\ 7 & 1 & 3 \\ 5 & 0.333 & 1 \end{pmatrix} \begin{pmatrix} 0.073 \\ 0.643 \\ 0.282 \end{pmatrix} = \begin{pmatrix} 0.22 \\ 2 \\ 0.861 \end{pmatrix} = \lambda_{\text{max}} w \tag{4.9}$$

$$\lambda_{\text{max}} = \left[\frac{0.22}{0.073} \; \frac{2}{0.643} \; \frac{0.861}{0.282} \right] \div 3 = 3.058 \tag{4.10}$$

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1} = \frac{3.058 - 3}{3 - 1} = 0.029 \tag{4.11}$$

$$CR = \frac{CI}{RI} = \frac{0.029}{0.58} = 0.05 \leq 0.10 \tag{4.12}$$

Since the value of CR is less than 0.10, we can assume that the judgments are acceptable and subsequently the system is consistent. Afterward, the AHP is applied to rank the different hospitals, but before that, their inputs should be computed.

4.9.2 AHP inputs

We used data from November 13, 2015, terrorist attacks in Paris to test the usability of the proposed approach. We assumed that there are a total of 30 victims that should be evacuated in an interval of two hours, and seven hospitals activated by the White plan. To test the capacity of PROOVES to manage the resource allocation and the wait time, we supposed that all the victims have the same disease and subsequently need the same resources. More accurately, the victims were diagnosed as having cardiomyopathy and should be transferred to a hospital to receive cardiovascular surgery. First, the system starts by querying POLARISCO to find out the needed healthcare resources that should be available in the hospital. Figure 4.15 shows the SPARQL query and the obtained results. The needed resources for cardiomyopathy include in terms of staffing, a cardiothoracic surgeon, an anesthesiologist, and an operating room nurse, and an operating room equipped with a defibrillator and an anesthesia machine in terms of medical devices.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ero: <http://www.ontologyrepository.com/CommonCore/Upper/ExtendedRelationOntology#>
PREFIX ao: <http://www.ontologylibrary.mil/CommonCore/Mid/AgentOntology#>
PREFIX polarisco: <http://www.semanticweb.org/linda/ontologies/2018/11/POLARISCO#>
SELECT  ?organization_member_role ?Medical_device
      WHERE {polarisco:Cardiomyopathy polarisco:needs  ?act_of_treatment.
              ?act_of_treatment  ero:realized_by  ?organization_member_role.
              ?act_of_treatment polarisco:involve  ?Medical_device.
              ?Medical_device ao:is_used_by ?organization_member_role }
```

organization_member_role	Medical_device
Operating_room_nurse_role	Defibrillator
Anesthesiologist_role	Anesthesia_machine
Cardiothoracic_surgeon_role	Operating_room

Figure 4.15: SPARQL query and results of the needed resources.

Once the needed resources are known, it is time for the AHP preprocessing step. For each hospital, the system gets its resources and then checks the number of needed resources available in this latter, get its transfer time, and calculate the maximum wait time. These computed values represent the inputs of the AHP method (see Table 4.7).

Table 4.7: Criteria values of the different alternatives.

Alternative	Transfer Time	Availability	Wait Time
HIA Percy	50	6	135
HIA Begin	30	6	135
H Pitié-Salpêtrière	20	6	145
H Henri Mondor	45	6	135
H Saint Louis	10	5	155
H HEGP	45	5	135
H Beaujon	40	4	125

4.9.3 Alternatives ranking

The following process is repeated one-at-a-time until all victims will be evacuated. That is to say, a new request is generated each time a new victim will be evacuated. In the following, we explain in detail one of the tests.

Step six: Alternatives weights

The priority vector is calculated to rank the different hospitals. Table 4.8 represents the overall priority vector of the different hospitals with respect to the criteria.

Step seven: Alternatives ranking

Table 4.8: Overall priority vector.

Alternative	Transfer Time	Availability	Wait Time	Somme
HIA Percy	3,65	3,858	38,07	45,578
HIA Begin	2,19	3,858	38,07	44,118
H Pitié-Salpêtrière	1,46	3,858	40,89	46,208
H Henri Mondor	3,285	3,858	38,07	45,213
H Saint Louis	0,73	3,215	43,71	47,655
H HEGP	3,285	3,215	38,07	44,577
H Beaujon	2,92	2,572	35,25	40,742

Table 4.9 shows the ranking of the different hospitals. The hospital with the highest priority is the most suitable hospital to transport the victim vi at the time t. These results are displayed to the DSM to make his final decision and choose the hospital destination, which is "Beaujon Hospital" in this case. Once the choice is made, PROOVES updates the wait time of the hospital's resources that will be used.

Table 4.9: Hospitals ranking.

Ranking	Alternative
1	H Beaujon
2	HIA Begin
3	H HEGP
4	H Henri Mondor
5	HIA Percy
6	H Pitié-Salpêtrière
7	H Saint Louis

4.9.4 Discussion

Figure 4.16 depicts the evolution of the victims' wait time to use the needed resources in the different hospitals after the evacuation of thirty victims (30 scenarios). In each scenario, the system updates the wait time of the selected hospital so that it will be considered in the next iteration. In fact, we observe that the wait time increases, as the number of evacuated victims increases. This is the result of our choice of evacuating victims that suffers from the same disease in order to evaluate the system's capability to not overwhelm one hospital. The graph shows that the hospitals' wait time is balanced after almost every ten iterations. This is due to the number of hospitals and also to the number of available resources per hospital. These findings highlight clearly that the victims are transferred to the most appropriate hospitals and these latter are balanced. This can accurately enhance the reaction to the variation of the wait time, improve the victims' evacuation process, and reflects the operability of the proposed system. Moreover, the application of the AHP for selecting the most appropriate hospital can improve the quality of the results and shorten the decision-making process.

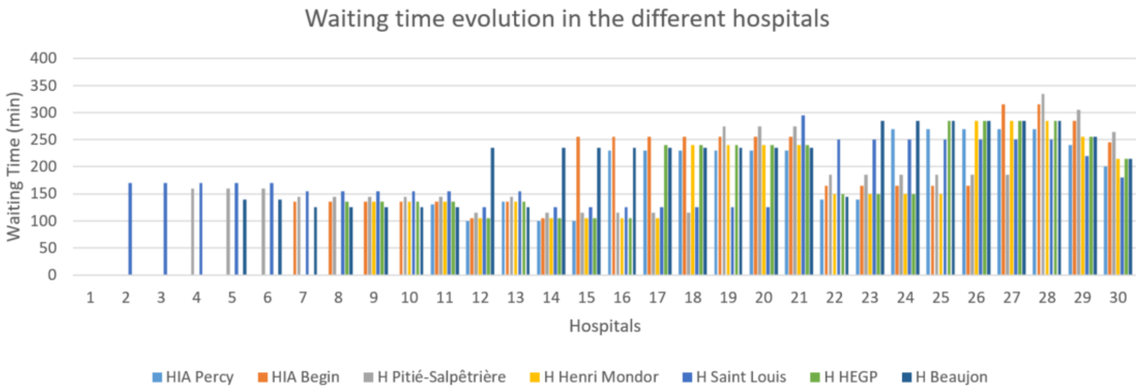


Figure 4.16: Results of the wait time evolution in the different hospitals.

4.10 Conclusion

The appropriateness of the victims' evacuation is essential to the quality of care and safety of victims. A complex and very important task is to make the best decision regarding which hospital a victim should be transported. A good evacuation strategy depends on a combination of resources availability, victims' wait time, and transfer time. However, decisions regarding the allocation of victims are complex due to the number of criteria that should be considered. In this chapter, we have proposed an ontology-based multi-criteria decision support approach for victims' evacuation. The provided algorithms enable addressing the dynamic changes in the availability of healthcare resources and wait times. These data are analyzed by the MCDM method AHP in order to obtain a ranking of the list of activated hospitals by the White plan from the most appropriate to the least appropriate according to the victim's needs. The AHP consistency analysis and evaluation index reveals that the approach is consistent. Moreover, the evaluation results highlight that the proposed system will contribute to an overall improvement in the efficiency of the victims evacuation process.

Conclusions

Disaster response is a highly collaborative and critical process that requires the involvement of multiple government agencies and emergency responders (ERs) ideally working together under a unified command to enable a rapid and effective operational response. Following the 9/11 and 11/13 terrorist attacks, and the devastation of hurricanes Katrina and Rita, it is apparent that the lack of relevant and timely information can adversely affect stakeholders' collaboration and decision making and subsequently the disaster response efforts. Within this context, empowering information exchange and information exploitation is the key factor for the success of large-scale operational disaster response. To tackle these problems, ontologies are increasingly used for their semantic explicitness and knowledge discovery in order to promote semantic interoperability across heterogeneous information and to support decision making.

In this thesis, our first research question was how to make the ERs' knowledge formalized enough for computed exploitation so as to interpret information in a semantically unambiguous way. In the literature, formalizing the knowledge of ERs is tackled by several research works. However, the proposed ontologies do not cover the operational vocabularies of the different involved stakeholders. Accordingly, the first contribution of this thesis is POLARISCO building. POLARISCO is a modular ontology that formalizes ERs' vocabularies focusing in particular on their operational knowledge. It embeds knowledge about stakeholders' data, services, processes, and business. It is built from an extensive literature review, in collaboration with emergency experts, and following a well-defined ontology development methodology. Moreover, POLARISCO development has considered a set of best practices including mainly the use of upper-level ontology, the reuse of existing ontologies, and the definition of the ontology's classes using the Aristotelian form. POLARISCO is composed of a reference core module named PCC (POLARISC Common Core) that englobes the general classes that all stakeholders share and seven ontological modules; firefighters module, healthcare units module, police forces module, gendarmerie module, public authorities module, messages module, and healthcare resources module. In fact, the definition of the PCC module and its reuse by the rest of the modules ensure more semantic interoperability among these latter. To link these modules, BFO (Basic Formal Ontology) was used as an upper-level ontology. Hence, POLARISCO is considered as compliant with other ontology thanks to the use of BFO.

POLARISCO can be more enriched to encompass the French doctrine towards covering knowledge about other stakeholders from other countries in order to be exploited in cross-border scenarios. Furthermore, it can be extended to cover other phases of disaster management like preparation, prevention, and recovery. Nevertheless, building large ontologies for complex information domain such as disaster management is time-consuming and necessitate a considerable involvement of domain experts. Accordingly, our future direction of work is to enrich and ameliorate PCC to be multilingual, open-access, and BFO-compliant reference ontology. It can serve as the overarching semantic basis for the development of more specific domain ontologies related to a particular context. Inspired by the successful initiatives of OBO

Foundry (Open Biomedical Ontology Foundry) and IOF (Industrial Ontologies Foundry), it will be stimulating if a Disaster Management Ontology Foundry (DMOF) initiative could be established to focus collaboration efforts on developing high-qualities reference ontologies that meet the needs of the different stakeholders of the disaster management domain. The main idea is to integrate existing ontologies and bring together the common entities used in this domain in order to provide a clear understanding of classes and relationships towards accelerating the development process of domain ontologies and improving its consistency. In this context, the hub-and-spokes model can be used to connect ontologies: the hub will contain disjoint reference ontologies that could be connected to other ontologies and make these latter more interoperable.

Developing a consistent ontology covering the entire disaster management domain will be a mountainous challenge. The benefit of using upper-level ontologies is ensuring a consistent and correct modeling style of the ontology. Consequently, different ontologies based on the same upper-level ontology could be integrated. In our context, PCC can be aligned and extended with classes from BFO-compliant domain ontologies. However, despite using the same upper-level ontology and basing on the best practices of ontology development, knowledge conceptualization is different from one ontologist to another. For instance, disaster is defined in POLARISCO as a subclass of “bfo: process”. In another BFO-compliant ontology proposed in the context of environmental monitoring, the same term is classified as a subclass of “bfo: disposition”. If these two ontologies will be integrated, the inconsistency will be immediately identified. Accordingly, the question that arises is how to integrate knowledge from different ontologies in a consistent manner?

The work accomplished in this thesis demonstrates the potential of ontologies building and exploitation towards enabling semantic interoperability between heterogeneous systems. Even presented as a key solution for interoperability and because of the diversity of the ontologies proposed in the literature, ontologies themselves are suffering from interoperability. Such diversity results in a lack of a standard that every ontologist should follow to develop their own interoperable ontologies. Therefore, future work should concentrate on exploring and defining the basic notions of ontologies’ interoperability. Accordingly, our future direction is to investigate an Ontology Interoperability Framework (OIF) inspired by the EIF (Enterprise Interoperability Framework) in order to give specific guidance on how to leverage interoperability between ontologies. OIF will consider different fundamental principles including ontology’s levels of abstraction, development process of the ontology (automatic, semi-automatic, or manual), tools, languages, ontology mediation techniques (mapping, alignment, matching, merging, and integration), model, meta-models, and méta-ontology.

Our second research question was how to ensure semantically interoperable information exchange among stakeholders. Accordingly, we proposed PROMES, an ontology-based messaging service on the basis of the EDXL standards. Using PROMES, it becomes possible for two ERs from different EROs to communicate meaningfully and with less ambiguity. ERs continue to use the terminologies to which they are accustomed, but PROMES semantically translate information and thereby enhance mutual understanding among EROs. Specifically, PROMES transforms the list of non-related technical terms and acronyms inputted by the sender to a message written in a formal language and semantically enriched basing on the receiver's vocabulary in order to reduce the ambiguity of the message. Based on the evaluation of the efficiency and accuracy of the semantic translation approach, the results of our study provided expressive performance and consequently can greatly improve the efficiency of inter-organizational communication.

As future work, further research to map the entire ontologies will be done in collaboration with emergency experts. Currently, we consider one possible kind of mapping between classes, which is "equivalentTo". We plan to take into account properties equivalence. Accordingly, we aim to propose a semi-automatic mapping between properties. It is interesting if the different properties will be automatically analyzed in order to find correspondences between classes. Then the mapping will be confirmed manually to ensure the correctness of the mapping results. For instance, when a new class is added in one stakeholder module, its properties will be analyzed to find out the possible equivalences with the rest of the ontology's classes. But, how new knowledge can be identified? It is interesting if radio communication records will be exploited to infer new knowledge to enrich the ontology and subsequently to improve the semantic translation of the exchanged information. This may open new possible directions for the exploration of today's advanced technologies of machine learning and voice synthesis.

Our third research question is "how to determine the most appropriate hospitals for victims' evacuation?". As a matter of fact, the number of victims to take in charge, the dynamicity of the resource allocation process, and the several criteria to consider may overburden the ERs. Accordingly, our aim was to support better decision making towards improving the process of victims' evacuation. To do so, we proposed PROOVES, an ontology-based multi-criteria decision support service. It searches for the most appropriate healthcare institution that can effectively deal with the victims' needs by considering the availability of the needed resources in the hospital, the victim's waiting time to receive the healthcare, and the transfer time that represents the hospital proximity to the disaster site. After a study of the different MCDM methods, the AHP method was chosen to rank the different hospitals. It ensures that the judgments are consistent and the final decision is well made through the consistency index computation.

To this end, the provided algorithms enable PROOVES to capture the occurring changes related to the waiting time of the used healthcare resources in the hospital. We performed various experiments to establish the validity of the proposed approach. The results showed that the assignment of hospitals was done successfully considering the needs of each victim and without overwhelming any single hospital.

The future directions of our work consist of, first, specifying the order in which the healthcare resources should be used to treat the victims. This may add more accuracy in the waiting time calculation. Second, it will be interesting if the variation of the transport means' availability is considered. Accordingly, PROOVES will be connected to the means management service of POLARISC. Moreover, the proposed multi-criteria decision support will be more effective if it considers the victims' survival estimation and how this latter may deteriorate to classify the priorities of the evacuation.

Once the whole POLARISC platform is developed, it will be tested by the different ERs during an inter-agency act of training to get their feedback and recommendations for further enhancements.

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Publications

- Linda Elmhadhbi, Mohamed-Hedi Karray, Bernard Archimède, J. Neil Otte, and Barry Smith. "A Semantics-Based Common Operational Command System for Multi-Agency Disaster Response". In:IEEE Transactions on Engineering Management(2020). Accepted.
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Abstract — The need to face the suddenness, complexity, and the chaotic nature of disasters makes disaster management more challenging. A streamlined operational response is crucial to handle the disaster effectively. It involves a complex network of diverse Emergency Responders (ERs) such as firefighters, police, healthcare services, and so on. In fact, many after-action reports from major disasters have pointed out communication difficulties and lack of information sharing among ERs as a major failing and challenge, and have expressed concerns over their abilities to collaborate. To overcome these issues, the main objectives of this thesis work are: from one hand, formalize the complex knowledge of stakeholders and resolve terminologies inconsistencies of the exchanged information in order to ensure mutual understanding among stakeholders, from the other hand, support ERs in evacuating victims to the most appropriate healthcare institution according to their state.

Keywords: Ontology, semantic interoperability, multi-criteria decision support, disaster response.

Résumé — La gestion opérationnelle des situations de crise est devenu une préoccupation majeure pour les pouvoirs publics. Elle nécessite la mobilisation rapide et la coordination des différents services de secours (Sapeur-Pompier, SAMU, Police, etc.). Selon les retours d'expériences, il y a un manque de coordination du fait de la diversité des acteurs intervenant sur le terrain, l'information n'est que très peu partagée et la communication n'est pas formalisée. Ces inconvénients conduisent au dysfonctionnement des réponses aux situations de crise. Afin de mieux répondre aux situations de crise, les principaux objectifs de ce travail de thèse sont : d'une part, formaliser les connaissances des acteurs métiers afin d'assurer un échange d'information sémantiquement compréhensible par tous les acteurs de secours, d'autre part, aider ces acteurs à évacuer les victimes vers les structures hospitalières les plus appropriées en fonction de leurs états pour une meilleure prise en charge.

Mots clés : Ontologie, intéroperabilité sémantique, aide à la décision multicritère, gestion des catastrophes.

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