Knowledge Fusion for Distributed Situational Awareness driven by the WAx Conceptual Framework

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ABSTRACT

Large crisis scenarios involve several actors, acting at the blunt-end of the process, such as rescue team directors, and at the sharp-end, such as firefighters. All of them have different perspectives on the crisis situation, which could be either coherent, alternative or complementary. This heterogeneity of perceptions hinders situational awareness, which is defined as the achievement of an overall picture on the above-mentioned crisis situation. We define knowledge fusion as the process of integrating multiple knowledge entities to produce actionable knowledge, which is consistent, accurate, and useful for the purpose of the analysis. Hence, we present a conceptual modelling approach to gather and integrate knowledge related to large crisis scenarios from locally-distributed sources that can make it actionable. The approach builds on the WAx framework for cyber-socio-technical systems and aims at classifying and coping with the different knowledge entities generated by the involved operators. The conceptual outcomes of the approach are then discussed in terms of open research challenges for knowledge fusion in crisis scenarios.

Keywords

Distributed situational awareness, knowledge fusion, WAx framework, crisis management, cyber-socio-technical systems.

INTRODUCTION

Modern society is continuously challenged by several crises due to natural events, such as earthquakes, avalanches, and pandemics, and to anthropic events, such as terrorist attacks, and to technological events, such as power blackouts. To cope with this variety of situations, several methods, models and applications have been developed by researchers and practitioners. Most of them assume that crisis management lifecycle consists of phases. Even if

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there is not an agreement on their number and the names, the following four are widely accepted ones: preparedness, response, recovery, and mitigation. Each phase requires the involvement of several actors that have different views and perspectives on the crisis situation to be faced. Gathering such knowledge and make it actionable requires to achieve a shared understanding among the different involved actors. Ontologies are good means to fit with this purpose. However, sometimes the different backgrounds of crisis operators or their different personal objectives hinder the creation of a common view. For instance, we can consider the situation where a rescue operator piloting a drone may cause damage to citizens and buildings during a rescue intervention and, consequently, wants to hide some information related to this accident to the operation manager. Even considering less extreme situations, shouldn't we start taking into account that sometimes an actual, complete, comprehensive and unique, shared awareness model of a crisis situation is rather hard to reach? And in this case, shouldn't we start designing crisis management systems that acknowledge the limitations of over-simplified assumptions and leverage on multi-perspective distributed data sources?

To this extent, we adopt the recently introduced WAx framework (Patriarca et al. 2021), developed as a conceptual artefact to deal with cyber-socio-technical systems. According to it, Work-As-Imagined, Work-As-Done, Work-As-Disclosed, and Work-As-Observed are different representations of the same work activity. The framework considers them as knowledge entities generated by different agents, such as sharp-end and blunt-end operators, and describes the relationships between them. Here, the idea is to apply it to explore distributed situational awareness among crisis agents, with the ultimate goal of modeling such variety of work representations, as they emerge from mutual knowledge conversions. We define knowledge fusion as the process of integrating multiple knowledge entities to produce actionable knowledge, which is consistent, accurate, and useful for the purpose at hand. We propose to use knowledge conversion maps as a means to represent the conversions of knowledge entities occurring during the knowledge fusion activity performed by an analyst, which could be either human or automated. Finally, we discuss some possible applications and some research challenges related to the adoption of the presented approach for crisis knowledge fusion to be addressed by the research community in the next years.

The rest of the paper is organized as follows. Firstly we present the related work in the area of conceptual modelling approaches to situational awareness. Then, we introduce a knowledge integration framework for situational awareness and some research challenges to achieve a model of distributed situational awareness. Lastly, the conclusions provide open questions and potential for future research.

RELATED WORK

Converting information into knowledge, knowledge analysis, knowledge integration, and reasoning are part of the knowledge fusion process, which is a precondition to achieve situation awareness (Smirnov and Levashova 2019) in a crisis management scenario. Ontologies aim at creating a shared understanding among the involved actors (Borglund 2017) and are considered as a valuable tool to improve situational awareness in large crisis scenarios. Furthermore, ontology integration techniques have now reached a good maturity level to the purpose of knowledge fusion (Osman et al. 2021). Even if building crisis ontologies is not an easy task that requires a huge endeavour and the involvement of domain experts (De Nicola and Missikoff 2016), there are already some proposals. Among the most recent works on crisis management ontologies, we cite: (De Nicola et al. 2019) that present an ontology for crises and emergencies impacting on critical infrastructures; (Coletti et al. 2020) that propose TERMINUS, an ontology for managing territorial knowledge and predicting hazardous situations; (Elmhadhbi et al. 2020) that present an ontology to improve information exchange among stakeholders; and (Chehade et al. 2020) that, similarly, propose an ontology to effectively handle communications in rescue operations. Finally, (Benaben et al. 2020) describe a comprehensive meta-model for crisis knowledge and data. All these works deal with information sharing during emergencies, which is considered as a relevant issue in crisis management (Van de Walle et al. 2016). However, with respect to them, we focus on the different perceptions of agents about the crisis situation and deal with how they are generated and transformed into different forms of knowledge.

MODELLING FOR KNOWLEDGE FUSION TO THE AIM OF DISTRIBUTED SITUATIONAL AWARENESS

This section presents our modelling approach for knowledge fusion finalized to distributed situational awareness. First, we provide more details on the WAx framework. Then, we describe how to apply it for modelling the knowledge fusion activity aimed at situational awareness during crisis management. Finally, we present a case study related to a simplified mountain rescue operation after an avalanche.

WAx Framework

The WAx framework (WAx: Work-As-x) (Patriarca et al. 2021) is a recent outcome of a research in the field of Resilience Engineering for industrial systems, built to support safety management and in general, performance

management of a work process. In the WAx, a natural science perspective was adopted to detail relationships and analyze types of transformation between different representations of work, or knowledge entity types, such as Work-As-Imagined (WAI), Work-As-Done (WAD), Work-As-Disclosed (WADI), Work-As-Observed (WAO), Work-As-Prescribed (WAP), and Work-As-Normative (WAN), extending the definitions of these concepts provided by (Moppett and Shorrock 2018). Briefly, the WAI expresses an expectation or a belief about how the work is conducted; the WAD is the actual activity carried out in the working environment, the WADI is a work description provided by a certain agent; the WAO is a model of how the work is interpreted by an observer, either directly or indirectly; the WAP encompasses the available prescriptive aspects of the work; and the WAN indicates the external norms such as international standards and governmental security procedures. The WAx knowledge entity types are instantiated by different *agents*, which could be grouped into two main categories, namely, blunt-end operators (BO), including managers and decision makers, sharp-end operators (SO), such as those performing the practical activities of the organization, and analysts. Indeed, the framework describes the *knowledge entities* enabling to distinguish the various agent perspectives of the same WAx entity type, e.g., WADI_{BO}, WADI_{SO} and $\text{WADI}_{\text{ANALYST}}$.

Furthermore, the WAx framework provides a rigorous conceptual structure to represent and analyze *knowledge dynamics*, i.e. how knowledge is created and converted by an agent (intra-agent modelling) and among the various agents of the system (inter-agent modelling). This accounts for types of knowledge flows that affect an agent mental model of the work (*tacit knowledge*), the way an agent represents and communicates work knowledge (*explicit knowledge*) to the external word, and how the agent acts in the real world. Moreover, the framework is recursive and fractal in its structure, so that it is adaptable for different granularity levels of analysis, fostering the understanding, modeling, and analysis of work practices in more general contexts, from an individual (human or autonomous machine) within a single organization to the whole organization in a inter-organizations collaborative work.

The description of the knowledge dynamics leverages on the concept of *knowledge conversion*, which has been deeply analysed in the organization management literature (Nonaka and Konno 1998). In particular, the knowledge dynamics of the WAx framework is founded on a conceptual model, which represents the basic types of knowledge conversion activities and how they apply to a WAx entity, throughout its tacit (WAx^{t}), explicit (WAx^{e}), and enactment (WAD) states. Specifically, for an individual agent the following activities are examined.

- *Introspection* refers to the conscious or unconscious examination of the agent's own WAx tacit knowledge. The effect may be a change on his/her mental model about the work.
- *Internalisation* is the agent's conversion from a WAx explicit knowledge (e.g., a document or a discussion) into his/her tacit knowledge.
- *Externalisation* is the expression of the agent's WAx tacit knowledge into comprehensible forms for other agents.
- *Conceptualization* is the creation of the agent's WAx tacit knowledge from real world actions or data.
- *Reification* is the agent's activity of applying his/her own WAx tacit knowledge to perform actions in the real world.

Additionally, the following two activities require interactions with other agents.

- *Socialization* refers to WAx knowledge sharing among different agents, so that this activity affects the WAx^{t} knowledge of the participating agents.
- *Combination* operates on the various individual explicit representations of WAx to create a new common WAx^{e}.

Guidelines for Modelling Flows of Crisis Knowledge

As mentioned in the introduction, crisis management is usually divided in phases with different goals ((Steen et al. 2021). For instance, the goal of the preparedness phase is to prepare to possible crises by means of simulated activities, training sessions and preparation of intervention plans including procedures, best practices, and actors that should be involved in a crisis scenario. The goal of the response phase is to coordinate and adopt all the measures required to react at the occurrence of a crisis. Finally, the goals of the recovery and the mitigation phases are, respectively, to reach at some degree the normal situation and to reduce the impact of a crisis in the long term. Each phase requires the involvement of several actors that contribute to the different phases by bringing their knowledge on the situation at hand and their experience on similar situations. Keeping track of the knowledge

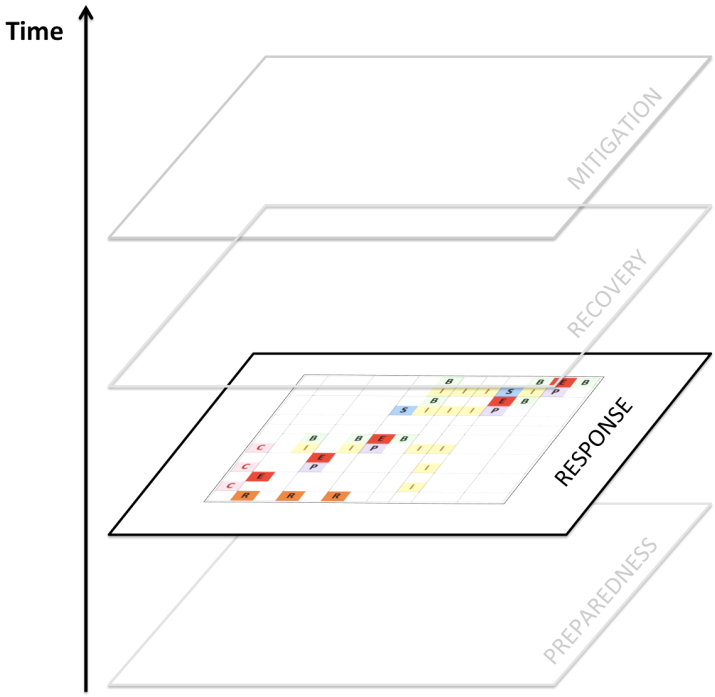

Figure 1. Crisis management lifecycle and knowledge conversion maps

flows among them is fundamental to ensure that the knowledge fusion activity required for distributed situational awareness is limitedly affected by communication and interpretation losses. To this purpose, here, we present how the WAx framework can be applied to reconstruct such knowledge flows by means of knowledge conversion maps, which show how a source knowledge entity is converted to a destination one. The final aim is to build a knowledge conversion map for each phase of the crisis management lifecycle. For the sake of clarity, this is sketchily depicted in Figure 1.

According to the WAx framework, the steps to build knowledge conversion maps for a specific case study are as it follows:

1. Identify key agents. Given a case study, blunt-end operators, sharp-end operators, and analysts have to be identified. These can be cyber agents (e.g., drones, software applications), humans (e.g., soldiers), or even animals (e.g., search and rescue dogs).

2. Identify knowledge entities. Relevant WAx knowledge entities concerning the crisis situation have to be identified for each agent.

3. Build knowledge conversion maps. The design structure matrix (see (Eppinger and Browning 2012)) is a valuable technique to model complex systems. Along this line, the knowledge conversion map is a matrix where the previously identified knowledge entities are placed in its rows and columns. Each row represents the target knowledge entity whereas columns represent the source ones. Hence, the resulting cells show the corresponding knowledge conversions, if any.

Case Study on Mountain Rescue

This subsection presents a simple exemplifying case study to show how a knowledge conversion map can be built in practice. This example concerns a mountain rescue operation. Due to extremely bad weather conditions followed by a temperature rise, an avalanche hits some houses close to the mountain. It is not known if (and how many) people were inside the houses and, hence, if there are casualties. Roads are also interrupted and rescue team operators cannot reach the buildings by car. The rescue operator manager decides to send a team of rescue operators, equipped with a flying drone. A search and rescue dog is part of the team, too. Meanwhile, the emergency room manager has the goal to reconstruct the overall situation and coordinate next intervention actions.

Table 1. WAx agents in the mountain rescue scenario

WAx agent role	*Agents*
Analyst	Emergency room manager
Blunt-end operator	Rescue operator manager (OM)
Sharp-end operator	Rescue operator (RO), drone, and search and rescue dog

According to the above-mentioned steps, first of all we identify the WAx agents (see Table 1). A rescue operator (RO), a drone, and a search and rescue dog are the sharp-end operators. A rescue operator manager (OM) is the blunt-end operator and the emergency room manager (ERM) plays the role of analyst, which will exploit the WAx entities generated by the other agents to reconstruct the situation.

The second step consists in identifying the involved knowledge entities. The WAD is the actual crisis situation that is only partially accessible. Since the crisis scenario is usually dynamic, unstable and unpredictable, the WAD is usually different from what is imagined by the different agents. Each agent has its own view (i.e., its own WAI) on the crisis situation. Hence, there are: the WAI_{Dog}, the $\text{WAI}_{\text{Drone}}$, the WAI_{RO}, the WAI_{OM}, and the imagined reconstructed situation by the emergency room manager (which is the WAI_{ERM}). Then, there are different WADI_{SO} generated in different forms by the sharp-end operators involved in the rescue operation. For instance, the search and rescue dog gives alert signals to the rescue operators by barking (i.e., WADI_{Dog}). The rescue operators receive data from drones (i.e., $\text{WADI}_{\text{Drone}}$) and combine this information with their perspectives on the situation. Finally, they periodically send reports to the rescue operator manager and the emergency room manager by mobile phone calls and sms messages. The WADI_{BO} is the perspective on the crisis scenario of the rescue operator manager (i.e., WADI_{OM}). He/she receives field information from the RO and interprets it through his/her past experience on mountain rescue interventions, his/her knowledge of rescue operation procedures (i.e., WAP) and of norms (e.g., drones cannot fly over population centers without prior authorization). The last knowledge entity here considered is the $\text{WADI}_{\text{Analyst}}$-of-WAD, which is the reconstructed situation as done by the emergency room manager. This is originated by a knowledge fusion activity that should takes into account all the different knowledge entities generated during the on-field operations.

The third step consists in building the knowledge conversion map. The actual crisis situation represents the real world together with the activities of the sharp-end operators. Limited to the rescue intervention, it can be considered as a reification of the WAI_{Dog}, the $\text{WAI}_{\text{Drone}}$, and the WAI_{RO}. Conversely, these knowledge entities are the result of a conceptualization activity starting from the actual crisis situation. The WAI_{Dog} is originated from an internalisation activity of the WAP. Whereas the $\text{WAI}_{\text{Drone}}$ is the result of the WAP, in the form of software code required to its functioning. Similarly, the training of the activity can be considered as the the means to teach the dog how to behave in similar circumstances (i.e. again the WAP). Hence, the explicit knowledge entities generated by the sharp-end operators are the WADI_{Dog} (e.g., the alert signals given when it finds a victim), the $\text{WADI}_{\text{Drone}}$ (e.g., the pictures of the impacted area), and the WADI_{RO} (e.g., communications between the rescue operator and the rescue operation manager and the emergency room manager). The WADI_{RO} is periodically updated and it is also the result of a combination activity starting with the $\text{WADI}_{\text{Drone}}$ and the WADI_{Dog}. The WAI_{OM} is the result of an internalisation activity of the WADI_{RO}, the WAP, and the WAN, a socialization activity with the rescue operator, and introspection. The WADI_{OM} is an externalization of WAI_{OM} and is periodically updated depending on the new occurrences of the WADI_{RO}. The imagined reconstructed situation of the emergency room manager is the result of an internalisation of the WADI_{RO}, the WAP, the WAN, and the WADI_{OM}, a socialization activity with the rescue operation manager, and of an introspection activity. Finally, the disclosed reconstructed situation is originated from an externalisation of the emergency room manager, and a combination activity involving also the WADI_{RO} and the WADI_{OM}.

Figure 2 depicts the ideal knowledge conversion map for the mountain rescue case study. In general, since the number of involved agents and knowledge entities increases in more complex scenarios, it is worthy to assess the differences between the ideal knowledge conversion map and the actual one to assess potential lack in the communication flows.

RESEARCH CHALLENGES FOR DISTRIBUTED SITUATIONAL AWARENESS

In this section, we highlight a plan of research activities towards knowledge fusion for situation awareness leveraging on the presented instantiation of the WAx framework. We envisage that the following steps should be accomplished.

1. Building a platform to manage the plethora of WAx knowledge entities referring to the same situation from different angles. To this aim, the platform should support building knowledge upon entities of various nature

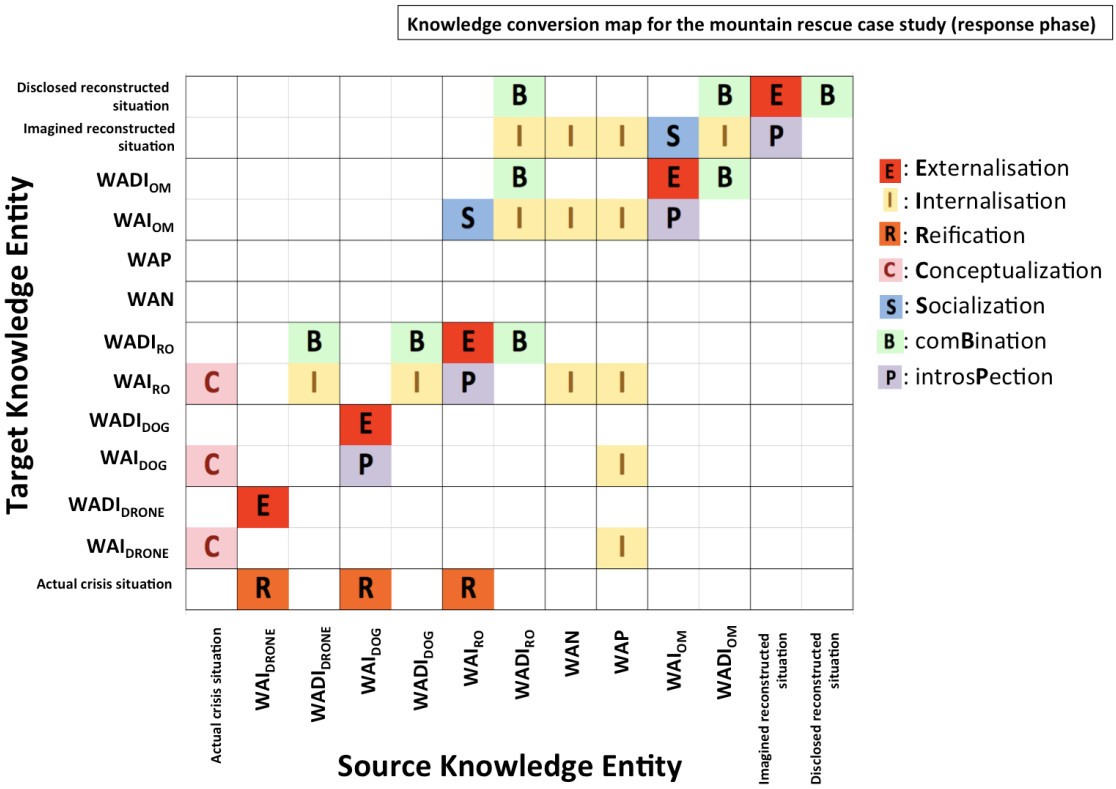

Figure 2. Knowledge conversion map for distributed situational awareness in the mountain rescue case study.

and/or structure (e.g., data, video, process models, free text) in order to realize situation-specific knowledge conversion maps.

2. Identifying automatic approaches to support detection of the inherent coherence of WAx knowledge entities from their individual semantics, as a precondition for knowledge integration.

3. Reconstructing the situation as result of a knowledge fusion activity, performed by an analyst or by means of automatic techniques, based on one or more instances of knowledge conversion maps.

4. Analysing the situation by means of formal models to identify, for example, flaws in the communication or in the coordination of the rescue activities. Ideally this analysis could be semi-automatic to shed lights on communication patterns that do not respect a certain set of rules.

CONCLUSION

The effectiveness of distributed situational awareness in large crisis scenarios impacts crisis management performance. Achieving a deeper understanding of knowledge flows between agents is a precondition to avoid a lack - or mis-interpretation - of information provision from sharp-end operators to the agents in-charge of reconstructing the scene. In this paper, we presented an approach to represent such knowledge flows by means of knowledge conversion maps that exploit the WAx framework for cyber-socio-technical systems. Future research activities will be devoted to define methods and tools capable to make reactive and proactive usage of such maps with the ultimate goal to support crisis management.

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