Actionable Situation Awareness: Supporting Team Decisions in Hazardous Situations

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ABSTRACT

Situation Awareness (SA) has been recognized and studied as an important requirement for an effective task performance of first responders. The integration of increasingly advanced sensor and artificial intelligence technology into the work processes affects the building, maintenance, and sharing of SA. Connecting SA to decision-support models provides new possibilities for the development of *actionable SA* (aSA), entailing information that guides the momentary decision-making processes of the concerning actors. In the European ASSISTANCE project, we develop an aSA module that displays information about gas distributions, its current and predicted future states (e.g., entailing risks of breathing-in of toxic gases), with references to effective decision-making *patterns* for this situation. The aSA model is continuously updated based on sensor data. This paper gives an overview of this aSA module for chemical hazard prediction and corresponding display, and presents initial team design patterns that will be integrated into this display to support its actionability.

Keywords

Situation awareness, actionability, decision support, chemical hazard.

INTRODUCTION

First responders (FRs) face large natural and man-made disasters (e.g., large wild fires, terrorist attacks, industrial incidents) that put their own lives and those of thousands of others at risk. These incidents usually take place in situations that are dynamic and vague. When FRs respond to an emergency call, they have to quickly understand what is going on, what the source of danger is, how to mitigate the danger and not lose track of how the situation is evolving. They need to have good situation awareness (SA) to mitigate the threat while keeping themselves and civilians safe. To do this, FRs need not only to have a perception and comprehension of the current situation, but also need to be able to project the current status into the future (see also (Endsley 1995)) and know what it means for their own decision-making and team communication.

The ASSISTANCE project[1] aims to develop tools that increase FRs' SA. ASSISTANCE proposes a holistic solution that adapts a well-tested SA application as a core of a wider SA platform, capable of offering different configuration modes for providing the tailored information outcome needed by each FR organization, while they work together mitigating the disaster (Perez et al. 2020). One of the new modules that will be integrated into the SA platform is a chemical hazard module that calculates potential hazard footprints, presented on a map, with continuously updated measurement from external chemical sensors. In addition, the output is continuously adapted and adjusted based on real-time information from sensor-data, meteorological data, and input by FRs.

[1]assistance-project.eu

A lot of research has been done on supporting (individual) SA for FRs (e.g., (Yang et al. 2009)), often focusing on SA building and maintaining, without including explicit support for decision-making, which overlooks the fact that people in different roles may want different information in different formats at different times (Zade et al. 2018) and the perspective of multi-agency emergency response which includes for example shared authority, dispersed responsibility and resources that are geographically spread out (O'Brien et al. 2020).

In this paper, we present an *actionable SA* (aSA) module that supports FRs in understanding, assessing, and predicting hazardous situations and decision-making by means of making teaming patterns, responsibilities, tasks, and dependencies between team members explicit, thus supporting *actionable* SA for FRs. To establish (individual) SA for the FRs, a chemical hazard module has been implemented, which is updated by real-time measurements and input from FRs, presenting the distribution of gas clouds on a map, and taking the inherent uncertainty of measurements and predictions into account. This module has been developed in close cooperation with FRs. It is designed as an adaptive intelligent system, acting as an artificial team member, to further support FRs in their decision-making according to their role, goals, and changes in the environment. We propose to specify these teaming aspects with Team Design Patterns (TDPs), and present a first example of a specification for decision-support.

SITUATION AWARENESS AND ACTIONABILITY

Since the 1980s the interest in situation awareness has been growing and even though the research into this construct started in military aviation, it has expanded into many critical domains that involve people performing tasks in complex situations (Salmon et al. 2006).The most prominent theory within the situation awareness literature is Endsley's model of situation awareness (Endsley 1995). The formal definition of Situation Awareness (SA) is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley 1988). This formal definition breaks down into three separate levels: perception, comprehension and projection. The first level of SA, *Perception* relates to observing critical information and cues in one's surroundings. Level 2 of SA, *Comprehension* refers to integrating perceived elements to an understanding of the situation. The third and highest level of SA, *Projection*, refers to the ability to anticipate the near future based on information of level 1 and 2. Level 3 enables the operator to understand which possible actions can lead to the desired outcome. In this approach SA is viewed as a product and state of knowledge in the individual's cognition. That means that the process of acquiring SA is distinguished from 'having SA'.

As research interest in SA grew, it expanded from the individual level to the team level. Definitions of SA came to reflect this expansion, e.g., to be "the shared understanding of a situation among team members at one point in time."(Salas et al. 1995). This view represents a significant departure from the individualistic models of SA rooted in cognitive psychology. It can also include the notion that SA can reside in human as well as non-human (technology) agents, which is becoming increasingly important given technological advances such as artificial intelligence and advanced automation, and so too is the notion of multiple 'agents' cooperating over time in order to remain coupled to the dynamics of their environment (Stanton 2016; Stanton et al. 2017).

Zade et al. (2018) explores approaching this problem from a different perspective, one of *actionability*. This approach is based on delivering the right information to the right person at the right time. The goal is to help FRs deal with the persistent challenges of information overload, limited organizational capacities, and the time- and safety-critical nature of their work. They investigated this in the context of social media data for first response and found that FRs already usually look at data from an actionability lense. All FRs in their study had mechanisms for thinking about how they prioritize information around what could be acted upon. Different FRs valued different kinds of information; actionability varied across role, contextual factors, and format. These results show that new, improved, responder-in-the-loop solutions that adapt to the needs of specific FRs are needed to optimally support them in their task and roles. Instead of systems that 'just' display relevant information to support SA, *actionability* could be achieved by introducing adaptive intelligent systems (i.e., intelligent agents) that can function as an artificial team member to adapt to the information and communication needs of the FRs. As team members are interdependent, they have to organize or coordinate their joint activities; hence, an (artificial) team member needs the ability for both task-work and teamwork (Bradshaw et al. 2011). Coordination within a team benefits from successful communication, where needed information is anticipated and shared proactively (Demir et al. 2017). Teamwork between humans and AI is not straightforward to implement into a (semi-)autonomous system (Diggelen and Johnson 2019). Although a lot of research has been focusing on describing requirements and guidelines for agents as teammates (e.g., (Klein et al. 2004)), the implementation remains difficult and conventional interaction design methods fail to adequately address the capabilities of intelligent systems. Team Design Patterns (TDPs) attempt to fill this gap and provide the means to capture human-agent teaming processes, to explore how agents can be designed as adequate team members, and to contribute to team performance, resilience and cohesion (Diggelen

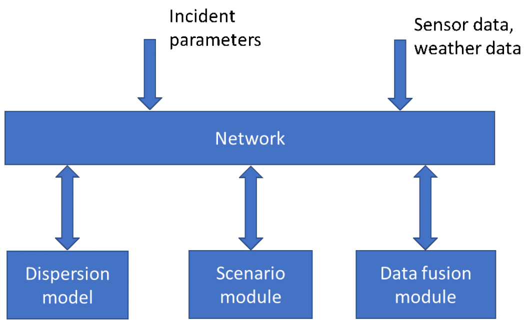

Figure 1. Overview of the components of the chemical hazard module.

and Johnson 2019). These TDPs can be seen as templates that can be re-applied to solve similar problems. A variety of application domains have used design patterns as a tool because they offer a good way of sharing and structuring design knowledge (e.g., interface design patterns (Van Welie et al. 2001), educational design pattern (Goodyear 2005)).

SITUATION AWARENESS SUPPORT FOR CHEMICAL HAZARD PREDICTION

In the ASSISTANCE project, we develop different modules that form the ASSISTANCE support tool for FRs. In the following, we take one of the modules, the chemical hazard module, as example to show how SA is supported, and in how the module is being improved to actually achieve *actionable SA*. First, an overview of the chemical hazard module is given. Afterwards, we describe how FRs have been involved in the design and development process, and the results of a first usability test.

Chemical hazard module

The *chemical hazard module* is designed to assist FRs when mitigating an incident that involves gas exposure. It provides operators with SA about the position of toxic gas clouds after accidental releases and calculates the probable distribution of the gas. The chemical hazard module calculates potential hazard footprints, presented on a map, based on user input describing the type of hazard. The output is continuously adapted and adjusted based on real-time information from sensor data, meteorological data, and input by FRs. It produces and shows the most likely position and size of the cloud, but also the uncertainties in position and size, which are due to uncertainties in e.g. the amount of released gas, the wind direction and wind turbulence. This helps the FRs understand where to be careful to avoid the toxic hazard and where to measure the gas concentrations to establish the actual gas concentrations that occur.

For an overview over the module's components, see Figure 1. Model calculations are done at three levels:

1. Core dispersion calculation (of a single plume) in the *dispersion model*.
2. Ensemble calculations (taking uncertainty in inputs into account) in the *Scenario module*.
3. Data fusion using measure data to reduce uncertainty in the *Data fusion module*.

In the following, the different components are described in more detail.

Dispersion model The central part of the hazard module is a dispersion model which is implemented as a web service and can be accessed through a web browser. In the map-based user interface, the operator must enter just a few very basic inputs to obtain a first sketch of the hazard area. In fact, indicating only the location of the accident from where the gas cloud is emitted is sufficient to start a first calculation and to get a first model output. The interface shows a template on the map as a first indication of where the hazard might be going (see Figure 2).

The meteorological circumstances are retrieved in real-time from an external server. The operator does not need to spend time finding out the wind direction and speed at the accident location. Other important dispersion parameters like atmospheric stability and surface roughness can be modified and have significant influence on the calculation results. Based on this additional data, new dispersion calculations can be started and a more accurate picture is presented, showing the length and width of the gas plume as contour lines for 3 levels of toxicity: the life threatening level, the potentially harmful level and the discernible level (see Figure 3).

Figure 2. Template view of the gas cloud distribution.

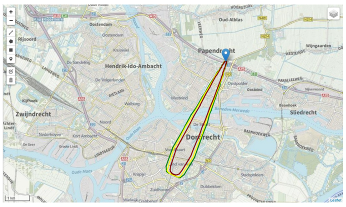

Figure 3. Contour view of the gas cloud distribution.

Figure 4. Ensemble view of the gas cloud distribution.

Scenario module All input variables that are used to calculate the contours have a certain inaccuracy. Many of the source parameters, like the release rate or released amount, the location and the time when the release started, are estimations by the person who reported the incident. Other parameters like the wind speed, direction and atmospheric stability are obtained from model predictions that also have an inherent inaccuracy. These uncertainties need to be taken into account for the calculations. For each of the input parameters, a distribution type and distribution parameters are assumed. These distribution specifications for each parameter are used to generate sets of N values that represent the distribution. From these sets of values, combinations are made to form N random input scenarios. Each of the scenarios is calculated by the dispersion model and results in a set of plume trajectories with associated contours of the hazardous concentration levels. The N sets of contours form an ensemble of equally likely realizations of where (and how large) the gas plume may be (see Figure 4). Based on the calculated ensembles, it is possible to show not only the most likely (expected) position and size of the cloud, but also the areas within which the cloud will be with a certain level of confidence, e.g. 90 % certainty.

Data fusion module Concentration measurements made in the field can be used as input to the model and improve the results of model calculations. For each concentration measurement value, reported for a certain position and time, a 'likelihood of correspondence' value is calculated for each member of the ensemble, based on the difference between the calculated and the measured concentration at that location and time. This results in the assignment of probability values to all ensemble members; low probability values can be eliminated from the ensemble set, whereas remaining ensemble members (and their associated input parameter values) are reinforced by the actual measurements and are assigned a higher probability.

SA support The goal of the ASSISTANCE project is to support building and maintaining SA. Regarding the hazard prediction module, integrated into the general ASSISTANCE system, *Perception* is supported by the different measurements that can be taken, on different locations, by FRs and robotic systems. In addition, weather data, for example wind directions and speed, and location of the different actors is observed and presented on the display. *Comprehension* is supported by the integration of the different kinds of data and the calculation and presentation of the hazard cloud position. It uses sensor data to reduce the inherent uncertainty in its prediction. *Prediction* is supported by the model by providing a projection into the future, based on current data. The movement of the hazard cloud is predicted, and the uncertainty is presented. In addition, a time slider is available to see the development of the cloud in time.

Iterative development and evaluation

The development of the chemical hazard module has been done in close cooperation with FRs to make sure that the chemical hazard module is in line with the FRs' needs and use context. Several workshops and interviews were held with different groups of fire fighters, for example fire fighter teams that would be handling the situation on location, hazmat experts that are stationed at a distance and would be involved in large-scale accidents, and commanders and team leaders that would be mostly stationed in the command post at location. These different groups of FRs were introduced to the researchers' vision of the chemical hazard module and the ASSISTANCE goals, and the concept of the chemical hazard module. During these sessions, the researchers asked the FRs about their current practice of handling accidents with dangerous substances, their tasks and decision-making process, their information needs (which differ for the different roles), the communication that takes place, and their wishes regarding the module and SA building and maintenance. In addition, the module was used by the FRs in example scenarios to evaluate functionalities and display options.

Usability Test

Besides the workshops, interviews, and sessions mentioned above, an interim usability test with two FRs (both male, one of them hazmat Officer, the other an on-scene commander) was conducted to assess the current work, shed light on possible improvements, and determine next steps.

The tool was explained while the user was trying it out and also asking questions. Then, five tasks were given to verify that the tool was understood. These tasks included calculating a gas cloud for a location, changing automatic meteorological data to manual, deciding a safe way to get to the site, and change the visualization of the cloud. This was followed by playing a scenario in which a gas leak was reported. The FRs were asked to verbalize what they would do at each step with information. As the scenario evolved, it was assessed how the system was used and what issues arose. After the scenario was played out a last question round was performed in which the FRs were able to state what could be improved.

The usability test showed two aspects: (1) the FRs used the chemical hazard module as intended, as a means to gain situation awareness of the gas cloud and the predicted development of the gas distribution, and (2) the FRs need and wish a good situation awareness to better decide on follow-up actions.

Gaining situation awareness The FRs appreciated the module and different views on the hazard prediction. They understood how to interpret the visualization and were happy with the different possibilities. However, they stated that there should be differentiated between a standard and an expert mode, as some of the outputs might be interpreted incorrectly by non-experts. For example, the hazmat expert reported that he has experienced that the ensemble view which displays three clouds as possible deviations in the prediction of the hazard development (see Figure 4) has been wrongly interpreted by non-expert FRs to mean the general expected distribution of the gas cloud. As the missions are often stressful and dynamically evolving, there is no room for misunderstandings and explanations and according to the hazmat expert, non-experts should only see the easier-to-understand template view (see Figure 2).

Gaining actionability During the scenario, the FRs used the information presented by the chemical hazard module to identify a safe route to reach the incident site and to make assumptions about possible actions regarding vulnerable locations (e.g., hospitals or residential buildings). As the Hazmat Officer put it: "The whole reason that you want to see the cloud on a map is to see vulnerable spots to decide whether we should take action and for example evacuate particular parts of the surroundings." Moreover, the displayed cloud distribution was used to decide where to send FRs of the regional teams to do measurements in the affected areas. The Hazmat officer mostly used the 'contour' visualization of the cloud to aid his decisions (see Figure 3).

ACTIONABLE SITUATION AWARENESS

As described above, SA is not a goal in itself; the understanding and prediction of the situation is embedded in decision-making processes, communication with team members, and actions taken in the environment. At the same time, all of these activities lead to changes in the environment and the need of an updated SA of team members. As described above, the chemical hazard module supports individual SA. It displays data measurements and other information, an interpretation of the situation, and prediction of the future development of the gas cloud. In the following section, we describe first ideas to add to a model of (team) SA to support *actionable* SA. As a first step, we propose to use Team Design Patterns (TDPs) to explicitly design teaming aspects such as communication to support decision-making of FRs.

Team Design Patterns

With Team Design Patterns (TDPs) we provide the means to capture teaming processes and explore how agents can be designed as adequate team members. They help to identify how dynamic changes in the environment can be understood and adapted to as a team. It is a way to describe design choices regarding coordination, communication, and responsibilities. Compared to other modelling languages, TDPs provide a concise overview of the design of human-agent (or human-robot) teaming concepts (e.g. role and task allocations) and is explicitly intended to involve the various stakeholders in the design process. For that reason, the TDP descriptions or formalizations should be coherent and concise, *and* be presented in an easy-to-understand format. When discussing teaming aspects with end users, a graphical representation as described in (Diggelen and Johnson 2019) is particularly suitable. This graphical representation is less formally linked to software engineering concepts than representations in other modelling languages, such as UML or SysML; the advantage however is that the graphical representation

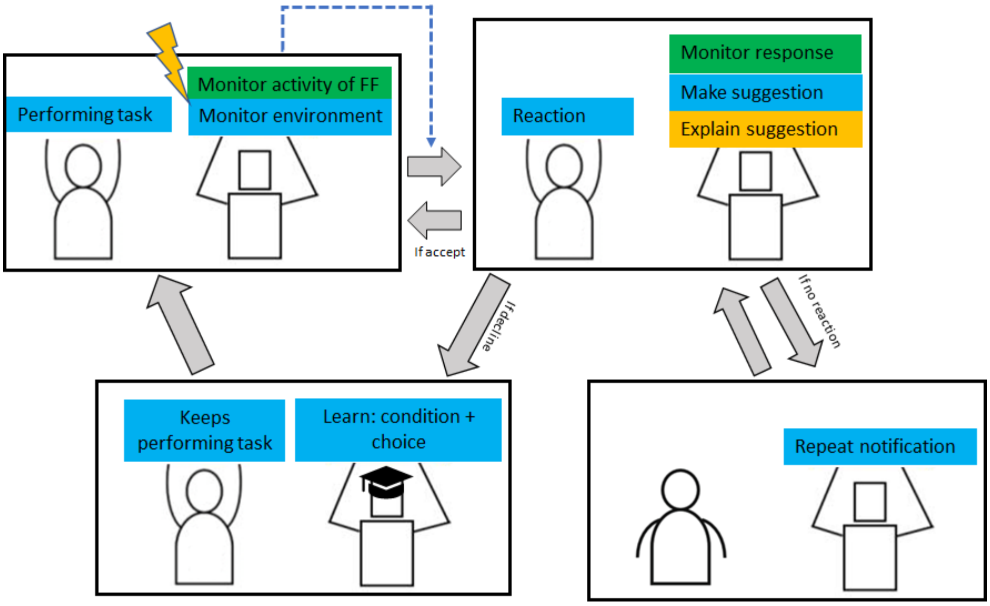

Figure 5. Example of Team Design Pattern *Actionability Supporting AI Agent*.

of TDPs is quite intuitive to understand and use, and facilitates discussion with end users. Recent research shows how to specify TDPs in more detail and make particular choices more explicit (Waa et al. 2020; Stijn et al. 2021), describing the different processes and design choices more formally.

With respect to the chemical hazard module, individual SA is supported by for example displaying the predicted position of a gas cloud and other data, such as the position of FRs, on the map. However, decision-making and coordination should also be supported. For example, if the wind direction changes, the module as specified above automatically recalculates the (new) predicted position of the gas cloud and displays it on the map. This functionality corresponds for example to having the responsibility to always present the current (and predicted) situation, without additional support for notification or advise. By specifying this choice by means of TDPs, the envisioned cooperation and responsibility mechanisms are made explicit.

In Figure 5 and Table 1, one possible TDP for an intelligent system with more decision-support capabilities is specified both graphically and textually. This example TDP shows the different responsibilities and the coordination between the human and artificial team member (in our case the intelligent chemical hazard module). It also offers the possibility to make advantages and disadvantages of this solution explicit. This TDP specifies of course only one possible design for supporting actionable SA; in this example, the designers chose to give the artificial team member the role of adviser. Other possibilities are for example to give the artificial team member the responsibility to execute actions in the environment itself, without prior approvement of a FR (e.g., communication acts such as notifications as well as coordination aspects such as re-positioning sensors to improve hazard calculations), or to specify situations in which notifications are sufficient. By making these choices explicit, consequences can be identified that have to be taken into account when designing adaptive systems.

Currently, we have identified several relevant TDPs which we have further specified in more detail. In addition, for these TDPs, interaction design patterns were specified and are being implemented to make specific design choices for particular interaction mechanisms, such as giving explanations. In Figure 6, a first version of the design of the interaction with an advising agent is shown. We are planning to evaluate a selection of different TDPs (specified and further translated into interaction design patterns for the chemical hazard module) with FRs to determine whether (1) the TDPs facilitate communication and evaluation of design choices regarding coordination, communication, responsibilities between different team members with FRs and (2) whether the different selected TDPs lead to a better *actionable* SA for FRs.

In addition, we will determine whether explicating TDPs in this generic way make them reusable for different applications, and whether generic knowledge about advantages and disadvantages can be gained and applied for different applications.

Table 1. Description of the TDP *Actionability Supporting AI Agent*.

Name	*Actionability Supporting AI Agent*
Description	The FR is performing a task when a change in the environment occurs. The artificial team member is monitoring the FR and the environment. It recognizes the change and initiates a recalculation of the model and its implications. It displays the consequence of the change, notifies the FR and gives a suggestion with explanation for how to adapt to the change. The FR decides whether the suggestion is valid and accepts or declines the suggestion. The artificial team member recognizes the conditions that where accompanied with the decline or acceptance of the suggestions and learns the applicability of this suggestion for similar future situations.
Requirements	The Human team member needs to have sufficient understanding of what is happening in the environment. The Artificial team member has to understand the implications of the change and provide a suggestion for actions. The Artificial team member has to be able to show the changes in the environment and to explain why the suggestion is made. The Artificial team member has to be able to learn from declined and accepted suggestions.
Advantages	+ The Human team member is assisted in the decision making process. + The human team member is notified about and shown dynamic changes in the environment. + The Artificial team member does not need to understand the implications of the proposed action, only the implications of the change that happened.
Disadvantages	- Constant suggestions might annoy the human agent. - Not well calibrated suggestions might confuse and distract the human agent. - Artificial team member might be take too long to learn how to adapt its suggestions.
Example	(a) The wind direction changes and the agent recalculates and displays the new gas distribution. It suggests to the Commander to get new measurements from specific locations to get more certainty. The commander can accept or decline (or ignore) those suggestions. The agent learns the certainty threshold that the commander would like to have. b) While the FR in the field is doing measurements, a warning is sent that the wind direction changed and the gas cloud moves towards the FR. The agent indicates that the FR should leave that area and indicates which direction to go. Again the firefighter can decline or accept.

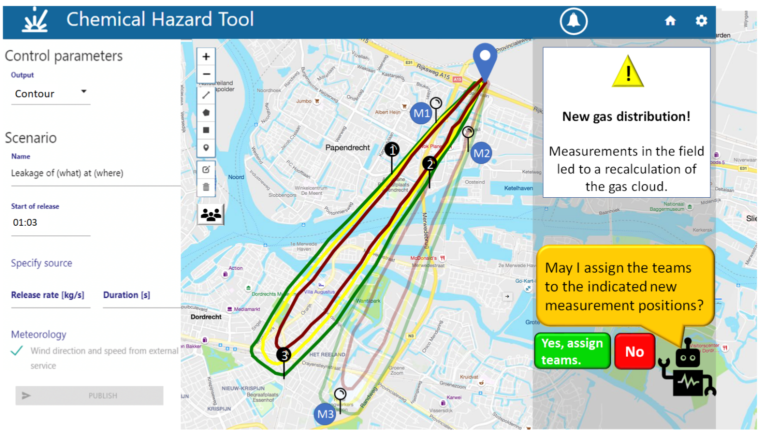

Figure 6. Screenshot of design of the interaction with an advising agent, including displaying consequences of a dynamic change in the environment, notification of the FR and giving a suggestion for an advised action.

CONCLUSION AND DISCUSSION

This paper presented a novel SA module that displays information about gas distributions, its current and predicted future states, with references to effective decision-making patterns for this situation. The SA module allows for development of actionable SA, which guides the FR in their decision-making process. The gas distribution model and corresponding display was iteratively developed, tested, and improved. Results showed that the model supports the SA building and maintenance of FRs. Furthermore, interviews have been held with FRs that provided important insights in the usefulness of the current module, and indications of future improvements. One of the topics that have been identified to further extend is the support in decision-making, adding *actionability*, thus connecting SA to Decision Support. First steps towards *actionable* SA have been described.

As next step, the use of TDPs as solution for making teaming aspects explicit will be evaluated with different FRs. First of all, we will evaluate how understandable TDPs are for FRs for designing cooperation; secondly, we will research which joint activities have to be coordinated when reacting to dynamic data, and how the collaboration within the team looks like. A set of TDPs will be further specified and implemented for particular situations and roles in the chemical hazard module and evaluated regarding decision support and building of SA. In addition, one of the next steps regarding future research of TDPs is linking the concepts to software engineering principles, to support the translation of TDP concepts into software concepts, while keeping the (graphical) representations intuitive and easy to understand and use.

Specification of TDPs is done in the design phase. However, optimizing the division of tasks between team members at a single point in time is not sufficient for effective team work, but can only be seen as the basis for further specification during implementation. It is hereby crucial to look at momentary task allocation, to consider how trust, cohesion, and coordination develops over time, and how members of teams dynamically shift between various arrangements of task allocation on the fly (Mioch et al. 2018). One way to do this are working agreements, which, in short, specify permissions, obligations, or prohibitions on agent behaviour. An example of a work agreement between the FR interacting with the chemical hazard module and the module itself could be that the chemical hazard module is obligated to notify a specific FR about the change in the movement of the gas cloud and that the module has to ask a FR for permission to set new positions for measurements. This work agreement could be adapted during run-time based on for example the task load of the specific FR, the position, or an estimated consequence of not notifying the FR. Future research will investigate the use of working agreements as one way to implement specific TDPs and evaluate the effects on (actionable) SA of FRs.

A lot of work has been done in the past on decision-support systems (e.g. (Loriette et al. 2019)). These systems mostly focus on the decision-making process, i.e., what information to take into account, how to reason about the information and how to present this information to the human decision-maker. TDPs specify teaming aspects such as responsibilities of for example decision-making and information sharing. The focus lies thus not on the decision-making process itself, but on the teaming aspects. However, for the future, we plan to link the TDPs not only to the chemical hazard module as described in this work, but apply them to other decision-making processes for FRs and other domains. In addition, we plan to investigate team learning and construct TDPs that include learning to improve the decision making, e.g., by providing experience feedback with the corresponding decision choices to further support *actionable* situation awareness (Loriette et al. 2019).

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