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Decision Support for Plan Adaptation in Unforeseen Situations

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ABSTRACT

Handling irregular phenomena might bring great complexity for involved teams. Variables considered for undertaking recommended procedures may yield many decision alternatives, which is challenging to deal with at planning time. Additionally, expectations regarding the phenomena handling may not match those observed. This means that the existing plan's application may become inappropriate, and teams must be creative in performing actions and decision-making. An approach for on-the-fly adaptation of plans aims to assist teams in identifying and diagnosing unforeseen situations, besides adjusting previously developed plans at runtime. This approach was evaluated through experiments in the emergency management domain, and the initial results indicate its feasibility in dealing with unforeseen situations while handling irregular phenomena in complex environments.

KEYWORDS

Decision-Making, Emergency Management, Improvisation, Knowledge Management, On-the-Fly Adaptation, Plans, Teamwork, Unforeseen Situations

INTRODUCTION

People and organizations increasingly need to handle irregular phenomena: a fact or event that happens or exists and is observed, but an understanding of what will occur during its existence is not clear in advance, being best explained only retrospectively (Merriam-Webster, 2021; Oxford, 2021; Taleb, 2007). These phenomena are usually found in complex, dynamic, and unpredictable environments, such as education, healthcare, lawsuits, and emergency management, and dealing with them is challenging.

Teams act over 3 phases when handling irregular phenomena: planning, enactment, and evaluation. During planning, the planning team devises a plan using existing premises and variables to design procedures and identify resources that, if followed and applied, should make the irregular phenomenon evolve into an expected situation (Alexander, 2016; Canton, 2019; Haddow et al., 2020; Phillips et al., 2016, Penadés et al. 2011; Shan et al., 2012). During enactment, the response team identifies the suitable procedures of the plan, depending on what is happening, and sequentially performs them until achieving the goal (Alexander, 2016; Baroni et al., 2014; Barthe-Delanoë et al., 2018; Carvalho et al., 2015; Comes et al., 2012; Glarum & Adrianopoli, 2019; Haddow et al., 2020; Phillips et al., 2016, Shan et al., 2012). Finally, during evaluation, the planning team collects information arising from the plan enactment to gain knowledge about the irregular phenomenon and uses successes and failures for the plan evolution, thereby providing a more suitable plan to deal with future phenomena (Canton, 2019; Haddow et al., 2020; Phillips et al., 2016).

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However, plan application is not always straightforward, and adapting to unforeseen situations becomes a task often performed in irregular phenomena (Baroni et al., 2014; Barthe-Delanoë et al., 2018; Böhringer, 2010; Carvalho et al., 2015; Cordeiro et al., 2015; Piccione & Pellegrini, 2020; Quiroz-Palma et al., 2020). Teams deal with uncertainty and unpredictability, with each action leading to several alternatives to handle. There is also pressure to make quick and critical decisions since the situations faced may be life-threatening and need immediate attention. Moreover, decisions are often made with incomplete information, bearing impacts on the phenomena response. Furthermore, any change requires teams to reevaluate the selected procedures (Alexander, 2016; Feng et al., 2016; Glarum & Adrianopoli, 2019; Lakshmanan et al., 2012; Ni et al., 2020; Ruiz-Martin et al., 2020; Smetana & Karda, 2019). Thus, the existing plan may become inadequate to be precisely applied, thus creating a need to make decisions and perform runtime adjustments.

The present research focuses on the plan enactment phase on the basis that there could be failures in diagnosing unforeseen situations and adjusting previously developed plans at runtime. A need to provide teams with information and tools that allows the adaptation of prior developed plans during their application in irregular phenomena is observed. They should be able to identify when the phenomena evolution does not match the expected one, to diagnose the plan adequacy to handle the observed evolution, and, if necessary, to adjust the plan to address the identified problems.

This paper details an approach for the on-the-fly adaptation of plans in unforeseen situations (Diirr et al., 2015; Diirr & Borges, 2016). This approach supports decision-making by providing the response team with information and tools that allow automatic identification of times when the phenomenon observed situation does not correspond to the expected one, diagnosing the plan adequacy to handle an unforeseen situation, and, if necessary, adjusting the plan to meet the current phenomenon evolution. We argue that this approach provides a more systematic way to deal with unforeseen situations, from their identification, diagnosis, and treatment, besides broader support for decision-making when handling on-the-fly adaptation of plans in complex environments. The approach is evaluated through experiments in the emergency management domain and is critiqued to guide further work. Initial results indicate the approach feasibility in dealing with unforeseen situations in irregular phenomena.

The paper proceeds as follows: Section 2 characterizes the unforeseen situations, details the difficulties faced to diagnose and handle such situations, and discusses related works. Section 3 describes the approach for the on-the-fly adaptation of plans in unforeseen situations, detailing how it supports teams during the plan monitoring, the unforeseen situations interpretation, and the plan adaption. Section 4 presents the experiments conducted in a rainfall scenario for evaluating the proposed approach, besides discussing the obtained results. Finally, Section 5 concludes the paper, highlighting the research contributions, limitations, and future work.

MANAGING UNFORESEEN SITUATIONS IN IRREGULAR PHENOMENA

When developing a strategy to handle emergencies, the planning team has many alternatives and combinations, which are difficult, if not impossible, to anticipate. It is common to manage subjective definitions, dynamic execution, unexpected restrictions, unpredictable decisions, and incremental response, thus reducing opportunities to devise a plan that specifies well-defined procedures to address all contingencies that may arise during the phenomenon evolution (Lakshmanan et al., 2012; Ni et al., 2020; Ruiz-Martin et al., 2020; Smetana & Karda, 2019). For example, the plan to deal with tsunamis at Fukushima nuclear plant predicted a maximum height of half of the estimated size of the tsunami that followed the earthquake (Acton & Hibbs, 2012). It means the accident could have been prevented if engineers had enhanced the plants' defenses against extreme external events, but nothing could be done following the tsunami. Even when carefully designed, the plan enactment is not always straightforward (Barthe-Delanoë et al., 2014; Cordeiro et al., 2015; Lakshmanan et al., 2012; Ley et al., 2014; Piccione & Pellegrini, 2020; Xie et al., 2012).

Figure 1. Unforeseen situation

Complex environments hinder finely detailed planning, making the addressed situation becomes clear only during its occurrence. Unplanned events are discovered at this point, which often affect the previously developed plan. These events may lead to unforeseen situations, which, in their turn, may lead to disruptions. Disruptions make it more difficult for previously developed plans to proceed as expected. As a result, they may become no longer applicable (Figure 1).

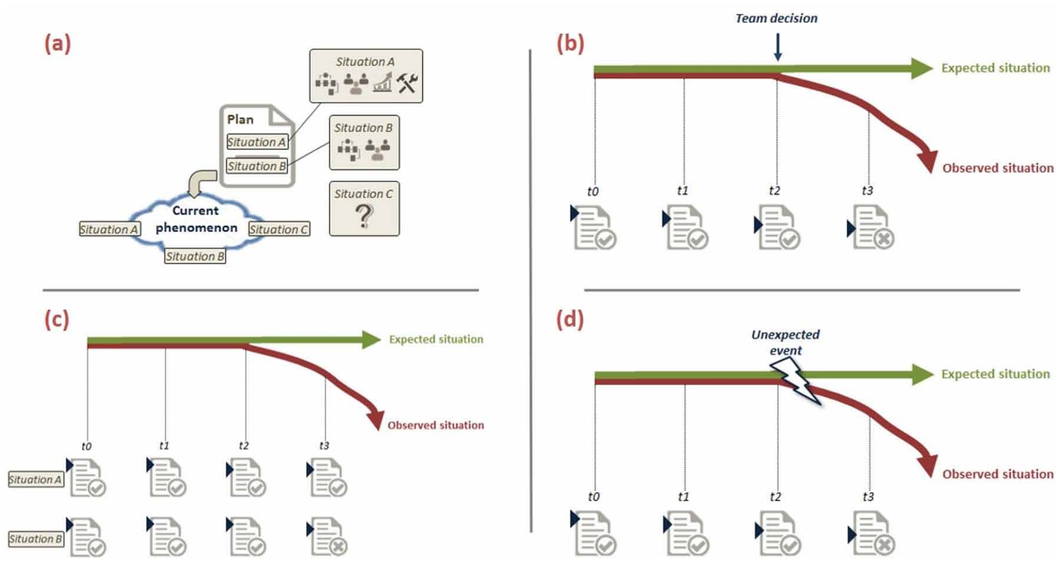
Unforeseen situations may arise due to various causes: the lack of knowledge that impacts plan completeness, such as the absence of some required resource or an entire procedure to handle a situation (Figure 2a); inappropriate decisions and poorly executed actions, which make the phenomenon evolve to a non-expected situation (Figure 2b); concurrency of procedures for handling simultaneous events, which may lead to the unavailability of prerequisites that are being used in another situation(s) (Figure 2c); and the occurrence of unexpected events that leads to situations not detailed during planning (Figure 2d). These situations compel the response team to observe the operating conditions, identify the new set of goals to be achieved, use creativity in finding alternative treatments, and make decisions at runtime. Thus, this situation can be solved, and the phenomenon handled (Alexander, 2016; Böhringer, 2010; Carvalho et al., 2015; Cordeiro et al., 2015; Glarum & Adrianopoli, 2019; Lakshmanan et al., 2012; Ley et al., 2014; Mendonça & Wallace, 2007; Savino et al., 2014; Xie et al., 2012).

To understand such situations, we interviewed obstetricians and anesthesiologists who perform labor in emergency rooms. Besides medical procedures detail several labor possibilities, they often need to be adjusted in emergency rooms. In this department, physicians must treat pregnant women with distinct medical histories (e.g., diabetes, high blood pressure, pre-existing illnesses, etc.) and experiencing different cases (e.g., preterm labor, abortion, uterine rupture, prolapsed umbilical cord, dead fetus, etc.). Hence, they have many alternatives to handle, usually make quick and critical decisions with incomplete information (e.g., patients never seen before, unconscious, lacking prenatal care), make claims about the application and effects of adopted procedures, identify alternative treatments from literature and prior experience, and constantly reevaluate the selected treatment considering changes in patient's condition.

Therefore, handling unforeseen situations is not trivial. The response team deals with a considerable amount of information, making variations that may be neglected or only evident when the phenomenon has already evolved considerably. Besides that, this team may not clearly understand what this unforeseen situation really is, thus hampering the diagnosis of its impacts on procedures. Moreover, runtime adjustments must be systematized to deal with unforeseen situations and change the plan for what is happening. The response team should decide on the level of adjustment required as well as to gain information and tools that effectively allow this adjustment. Hence, the difficulty in applying previously developed plans to irregular phenomena suggests the need to provide broader support when dealing with unforeseen situations, from its identification to the plan adjustment.

The authors claim that using knowledge arising from the phenomenon, which comprises the prior knowledge (plans, guides, response team's experience) and current knowledge (generated by

Figure 2. Unforeseen situations' causes



the phenomenon evolution and the consequences of plan enactment) (Diniz et al., 2005; Feng et al., 2016), may bring benefits for the on-the-fly adaptation of plans in unforeseen situations. This knowledge allows a better understanding of the ongoing phenomenon and provides solutions to the identified unforeseen situations.

Literature shows different uses of existing knowledge to handle unforeseen situations at runtime. Regarding identifying and diagnosing unforeseen situations, studies propose using emerging data to assess whether planned procedures are still valid for addressing the ongoing phenomenon. Barthe-Delanoë et al. (2018) automatically deduce the phenomenon current conditions based on data coming from the field and monitoring, which helps identify mismatches in the plan and supports the decision-making process for plan adjustments. Comes et al. (2012) use information of current emergency evolution for deciding whether the established scenarios are still valid, or the new information presents important facts that lead to the scenario updating. Martens et al. (2012) propose a case management system that analyzes the execution traces and case data to guide teams in controlling processes with unstructured segments of activities and reactions to exceptional situations, thus making adjustments when necessary.

Concerning the plan adjustment, studies suggest using previous phenomena to learn what has been done in similar situations. Chakaborty et al. (2010) propose a system for retrieving a set of cases with similar characteristics to the current conditions and adapting them to devise a viable solution for application. Martens et al. (2012) propose a system that identifies cases with similar characteristics to the current case, thus managers can learn what has been done and offer solutions from the actions taken in each case. Minor et al. (2014) allows creating and adapting workflows by retrieving previous adaptations from a case library, assessing such cases, and applying the most appropriate alternative in the current process. Ramirez-Marquez & Farr (2009) present a decision-making-based approach for identifying catastrophic scenarios and producing indices that allows selecting the most suitable scenario for disaster recovery plan development. Other studies provide recommendations on the following action from an analysis of what is happening. Comfort et al. (2013) use information about evolution to calculate which option may achieve the most effective result to handle urgent events. Dorn et al. (2010) analyze information describing ad-hoc processes execution to recommend the following action that matches the process execution's current situation. Also, there are proposals to configure a plan using context and data emerging from execution. Barthe-Delanoë et al. (2018) use deduced information to provide a range of adaptation solutions to support the decision-making process. Carvalho et al. (2015) and Nunes et al. (2018) propose to perform runtime adjustments in well-defined, repeatable, and little complex processes when managers identify any deviation during its instantiation to a specific context. Finally, improvisation may also be used. Ley et al. (2012) propose an IT structure supporting improvisation and collaboration of crisis management teams from the different organizations involved in emergencies. Mendonça and Wallace (2007) propose a cognitive model for improvisation to obtain a referent from declarative and procedural knowledge when a contingency that blocks the execution of a planned procedure occurs.

Although these studies describe proposals for managing unforeseen situations in complex environments, the authors claim that present research differs from the others in two aspects: (a) more appropriate support in the decision-making process for handling unforeseen situations as a whole, i.e., from identification, through the diagnosis of their impact on plans, to performing plan adjustments for handling the current phenomenon evolution; and (b) using both explicit and tacit knowledge when handling unforeseen situations to have enough elements for performing adaptations: the former allows identifying unpredicted events and provides inspiration for alternative actions; the latter is helpful in situations that may not bear a relationship with prior explicit knowledge, thus requiring methods for identifying, handling, and using it.

APPROACH FOR ON-THE-FLY ADAPTATION OF PLANS IN UNFORESEEN SITUATIONS

The proposed approach uses the knowledge arising from the phenomenon evolution to provide the response team with information and tools that allow the plan adjustment when an unforeseen situation occurs (Diirr et al., 2015; Diirr & Borges, 2016). By monitoring the selected plan, considering the situation awareness and predefined parameters, it is possible to identify unforeseen situations. Then, they are interpreted to assess if the plan is still applicable. If interpretation shows a disruption, it is necessary to adapt the plan, which response teams should apply (Figure 3).

Plan Monitoring

The response team makes decisions and acts following the developed plan. When using this document, the response team knows who is carrying out specific actions, the resources available, and coordinating all efforts. Besides the diversity of representations and the difficulty in formalizing plans in complex environments, it is possible to identify a set of common elements to describe them (Alexander, 2016; Bénaben et al., 2016; Ferreira et al., 2015; Guo et al., 2020; Penadés et al. 2011; Savino et al., 2014) (Figure 4): *action*, a task performed to achieve a goal, which takes the phenomenon from one state to another by changing the state variables values; *state*, variables that characterize the phenomenon at a specific moment, thus having associated values that may change over time; *resource*, necessary elements to perform an action or that influence its performance; *event*, which may occur during handling and has an impact on the state variables; and a *goal*, what should be achieved. These elements are not always formally structured, being in the response teams' feeling, but should be instantiated in plans for complex environments.

In parallel, current conditions are updated with information about the phenomenon evolution and arising from the plan application. It allows the response team to decide which parts of the plan they should perform at which specific moment and assess whether the plan still handles what is happening. The impact of the plan application and possible unexpected events should also be considered. Thus, the following information should be captured to characterize the situation awareness: *performed/remaining actions*; *people involved*, with details about their skills, location, and allocation; *required information*, with data regarding its updating, reliability, completeness, and availability; *required systems*, with data on their availability; *required material resources*, with data on available quantities,

Figure 3. Approach for the on-the-fly adaptation of plans in unforeseen situations

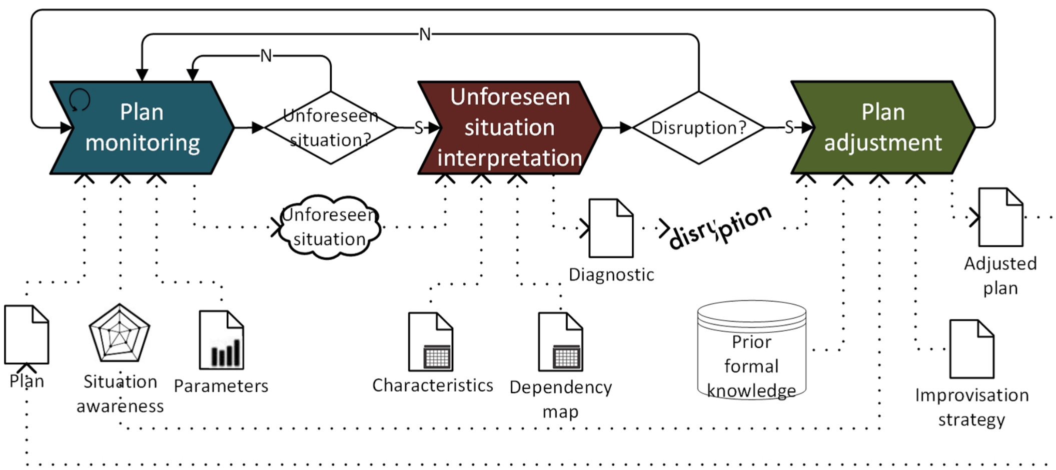
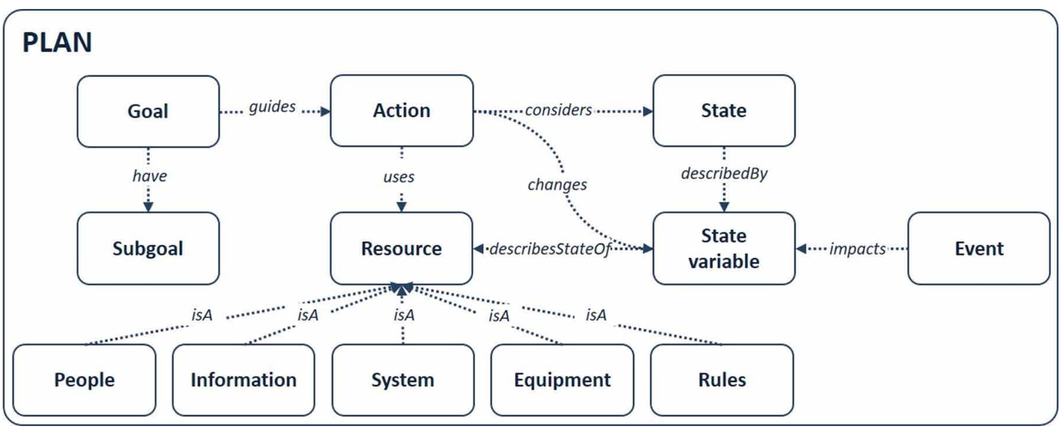


Figure 4. Plan elements



location, and allocation; *existing restrictions*; current *duration* of phenomenon handling; the actual *cost* of phenomenon handling; *action results*, to assess whether the expected results have been entirely/partially/not achieved; and *final goal status*.

Pre-established parameters help to identify inconsistencies between what is in the plan and what is happening. The approach suggests the establishment of (a) a set of critical state variables (those more likely to cause adverse impact if not properly handled or which must be a priority) and (b) validity ranges within which the conditions for handling each state variable remain valid. It is necessary to balance the strictness level for establishing these ranges: too rigorous ranges may generate more unforeseen situations and adaptation demands; too flexible ranges may make the plan ineffective. Both tasks are ideally performed during planning, but the response team should revise them during the plan enactment to guarantee their validity for the current reality.

The plan monitoring is an automatic comparison of these three components (plan elements, situation awareness, and pre-established parameters) to assess how far the values of each state variable in the plan are from those observed in reality. The comparison starts from the critical state variables and, after that, goes through the noncritical variables. If comparison finds significant variations (i.e., values outside validity range), an unforeseen situation is identified and must be assessed.

This phase helps the response team decide when a plan variation should undergo a deeper analysis and why this should happen. Moreover, as unforeseen situations are identified by comparing the expected and observed values of state variables, a decision to analyze the plan will be automatic, providing more agility in reacting to unforeseen situations since the parameters indicating the need for unforeseen situations analysis have been already defined.

Unforeseen Situation Interpretation

The response team must understand the unforeseen situation impact and decide what actions to undertake. Hence, interpretation begins with retrieving state variables showing variations and using a template to determine the type/impact of the unforeseen situation affecting them (Table 1). For instance, the table shows six unforeseen situations affecting the state variable “People involved” (“Insufficient people”, “Lack of required skill”, “Allocated to another action”, “Not found”, “More people” and “Early deallocation”) and the impact (positive or negative) that each of them causes on this variable.

After this, a comprehensive analysis is performed, which considers the impact of a state variable affected by the unforeseen situations on the other state variables (Table 2). For instance, an unforeseen situation harming the variable “Required material resources” causes negative effects on the state variables “People involved”, “Estimated elapsed time”, “Estimated cost”, and “Expected action result” (i.e., if there are insufficient material resources, people involved will do extra work, the phenomenon handling duration and cost will be higher, and it will be harder to achieve the expected results). A disruption is reported when a related variable is a critical one, or the observed values of the associated variables cannot handle the variation caused by the unforeseen situation.

Table 1. A non-exhaustive list of unforeseen situations affecting state variables

State variable	Unforeseen situation		State variable	Unforeseen situation	
People involved	-	Insufficient people	Required material resources	-	Absent
	-	No required skill		-	Allocated to another action
	-	Allocated to another action		-	Broken
	-	Not found		-	Not found
	+	More people		-	Lack of requirements
	+	Early deallocation		-	Out of date
Required information	-	Absent		+	More material resources
	-	Out of date		+	Early deallocation
	-	Unstructured	Estimated elapsed time	-	Expired
	-	Incomplete		+	Available
	-	Unreliable	Estimated cost	-	Lack of money
Required systems	-	Absent		+	More money
	-	Not working	Expected action result	-	% lower than expected
	-	Lack of requirements		+	% higher than expected
	-	Out of date	Existing restrictions	-	Unable to perform an action
	+	More systems		-	Unable to use resource

This phase helps the response team to decide on triggering adaptation procedures. A computational tool provides inputs for identifying unforeseen situations, classifying their impact on a specific state variable and on its related state variables, and indicating a disruption occurrence. The response team

Table 2. Dependency map

			Related state variables							
			People involved	Required information	Required systems	Material resources	Existing restrictions	Elapsed time	Estimated cost	Action result
Affected state variable	People involved	+						+		
		-		-	-	-		-	-	-
	Required information	+								
		-	-		-	-		-	-	-
	Required systems	+								+
		-	-	-				-	-	-
	Material resources	+						+		
		-	-					-	-	-
	Existing restrictions	+								
		-	-	-	-	-		-	-	-
	Elapsed time	+	+	+						
		-	-	-					-	
	Estimated cost	+	+			+				
		-								
	Action result	+	+		+	+		+	+	
		-	-	-	-	-		-	-	

has the expertise to use the available information and interpret it as a trigger for adjusting the plan. Therefore, both the response team and the computational tool support the decision-making.

Plan Adjustment

The response team aims to develop an operational plan to deal with the reported disruption. Hence, they perform various plan adjustments, ranging from specific changes, by repositioning existing plan elements or incorporating new elements into the plan, to a complete plan revision. Thus, the response team must understand the disruptions and access the available knowledge (plan, situation awareness, other plans, personal experience, etc.) for handling them.

After that, the response team may apply an existing alternative plan, which can be retrieved from a knowledge base, to provide a solution for the disruption. However, when it is impossible to find a plan with a viable solution, improvisation should be adopted. Improvisation involves recombining the available resources to create a solution to an unexpected change in the environment that teams could not anticipate and, due to this, there are no procedures for handling it (Lewis & Lovatt, 2013; Ley et al., 2014; Mendonça & Wallace, 2007). Therefore, the response team must improvise until (a) achieving the established goal or (b) reaching a situation that allows an existing plan application.

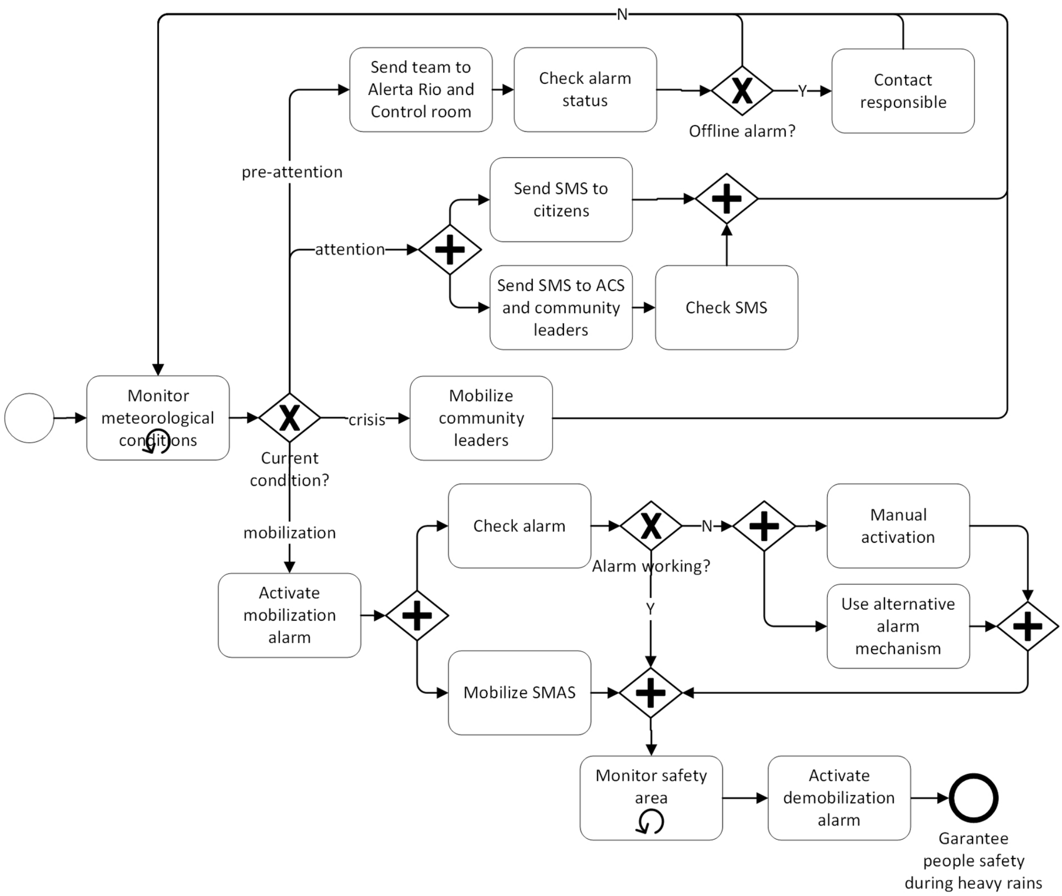
The response team also evaluates the solution's impact and selects the most suitable alternative for the ongoing situation. Moreover, as solutions come from different plans or prior experience, they may be incomplete or lacking structure for immediate application. Hence, the response team must analyze these solutions and represent them accordingly to the proposed plan elements.

As in unforeseen situation interpretation, decision-making involves the response team and a computational tool. The response team decides what needs to be adjusted (a specific part or the entire plan) to provide an operational plan for the faced disruption. When a more profound adjustment is required, this team determines whether (a) it can apply an alternative plan or (b) it must devise a new plan, either from an existing evaluated plan or improvisation. A computational tool provides alternative plans from a prior formal knowledge base and supports their adaptation to solve the faced disruption.

Proposal Evaluation

The approach was evaluated in a rainfall scenario. Rio de Janeiro is a region often exposed to heavy rain due to its geographical characteristics. Furthermore, a metropolis suffered from disordered growth, having several construction areas at high risk of landslides. Damage is acute during summer, when heavy or prolonged rain occurs, producing floods and landslides. To ensure the safety of people living in high-risk areas, the Civil Defense has established procedures for evacuation (SUBDEC, 2015a) (Figure 5).

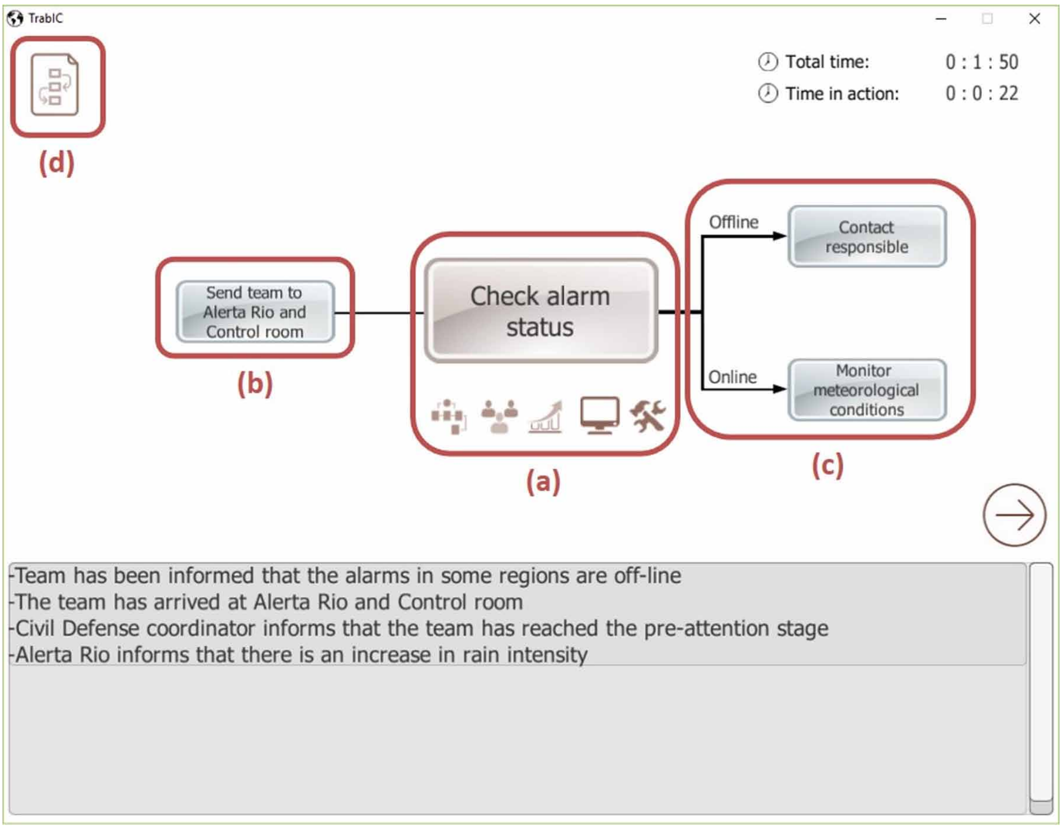
Figure 5. Contingency plan for heavy rainfall using BPMN (OMG, 2011)



As emergencies are unpredictable and life-threatening, it is not easy to evaluate an approach during an actual rainfall, being necessary to simulate this complex environment in a laboratory. Hence, the researchers interacted with governmental agencies, which examined the plan and provided additional information about what is usually done during heavy rainfalls; discussed goals to achieve, actions to take, resources, and resulting states from the actions execution; described events and situations often found; discussed problems response teams face; and provided historical information (SUBDEC, 2015b; SUBDEC, 2016). This information helped to devise the experiment scenario and a set of unforeseen situations. The researchers also invited people from investigated domain to participate in the two experiments: one at the Civil Defense of Niterói and another at the Graduate Program in Civil Defense and Security. Their experience in dealing with high-pressure events significantly contributed to our simulation and to obtain results close to reality.

Both experiments started with an overview of the rainfall scenario, and the tool participants should use to support decision-making. After that, participants started monitoring the plan, understanding which action is being executed (Figure 6a), what was done (Figure 6b), what can be performed next (Figure 6c), or accessing the whole plan (Figure 6d).

Figure 6. Plan monitoring



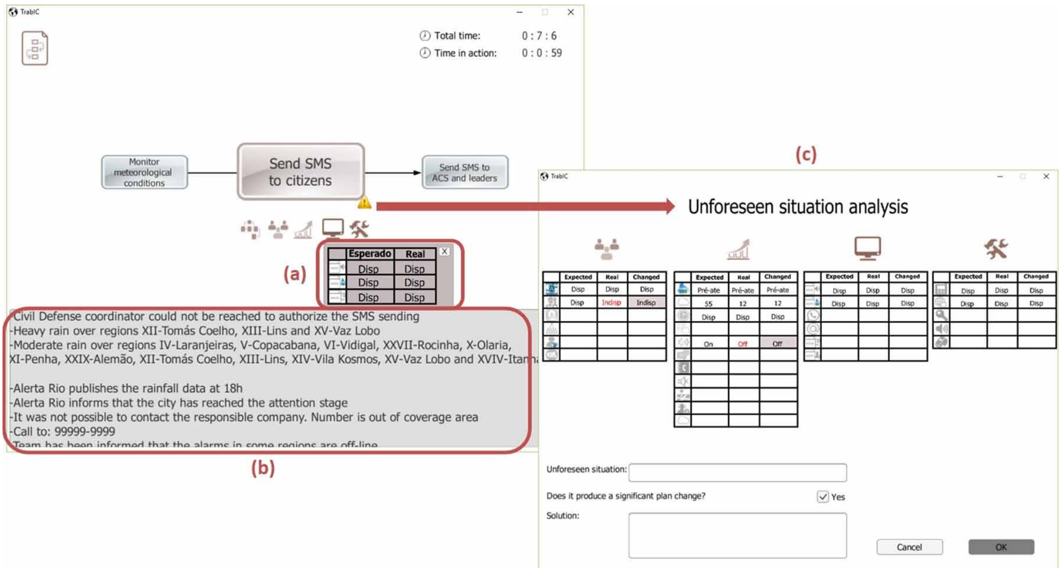
Participants could also access information about the current handling conditions (Figure 7a) and receive news from the response teams on the field (Figure 7b). The tool automatically compared the plan elements, situation awareness, and pre-established parameters to ensure that the suggested treatment is still suitable for the observed situation. Any inconsistency was treated as an unforeseen situation, being automatically shown to participants (Figure 7c).

As a result, participants provided a diagnosis of the unforeseen situation, comprising (a) the unforeseen situation faced, (b) if it led to a plan disruption, and (c) what should be done to solve it. Plan adjustment was beyond these experiments' scope, and it will be evaluated on a future occasion.

Data Analysis

Data gathered from experiments (recordings, notes, system logs, and questionnaires) and participants' experience in dealing with high-pressure events greatly contributed to our simulation, thus obtaining

Figure 7. Unforeseen situation analysis



results close to reality. The following subsections answer the research questions (Table 3), highlighting participants' contributions to support researchers' observations. Choosing a qualitative evaluation was due to the number of participants and experiments which were carried out.

Team Profile

All participants had some professional relationship with the emergency domain (Figure 8): they either assumed different roles within emergencies or participated in the graduate program focusing on training professionals to act in emergencies. They also had varying levels of experience in this domain, with most of them having dealt with high-pressure events for more than five years. Hence, despite being a small group, it adequately represents the structure and required roles for a response team in a control room handling the proposed scenario. Participants often dealt with high-pressure events and could handle a scenario describing a 1h event, of which the actual duration was about 8h.

Unforeseen Situations Identification

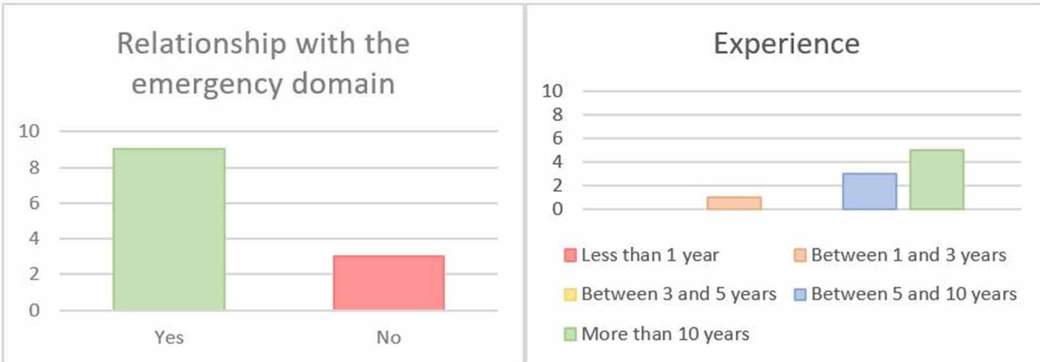
System log analysis showed that participants implemented half of the planned unforeseen situations. They did not implement other unforeseen situations because the experiment reached its planned duration. Also, participants identified all implemented unforeseen situations and, as soon as an unforeseen situation arose, participants identified it as a problem to be solved.

The questionnaire provided extra information on the participants' perception of unforeseen situations identification. The proposed plan elements facilitated actions understanding and monitoring, with participants reporting several benefits: *"It helps identify possible plan changes and standardize solutions that may become the operating procedure in the future"* and *"The graphical presentation of*

Table 3. Research questions

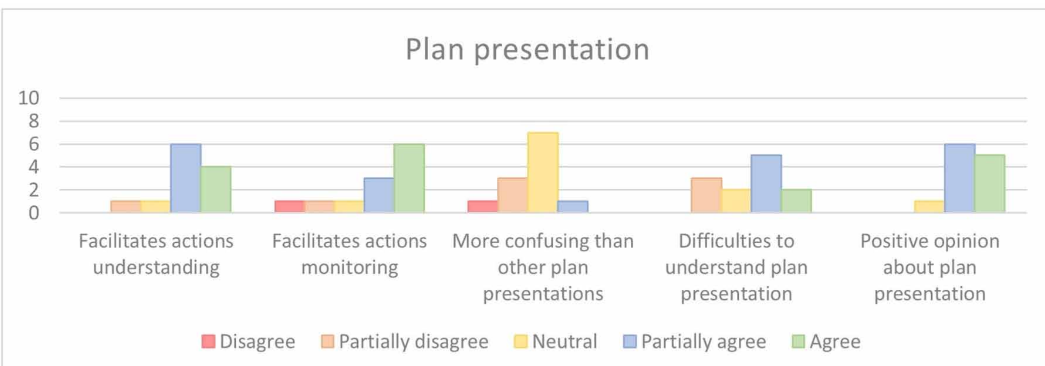
RQ1	How decision support mechanisms affect team performance during unforeseen situations identification?
RQ2	How decision support mechanisms affect team performance during unforeseen situations interpretation?

Figure 8. Participants' profile



the plan were positive". However, they also mentioned tool interface problems that could hamper the unforeseen situations handling: *"The tool does not allow correcting or adding additional information"*, *"The plan should present actions to be taken in each situation"*, and *"The interface should be more user-friendly to explore further possibilities that the plan offers"*. These results show a need for training on the proposed plan representation so participants can understand this perspective change better and indicate the need for tool interface adjustments (Figure 9).

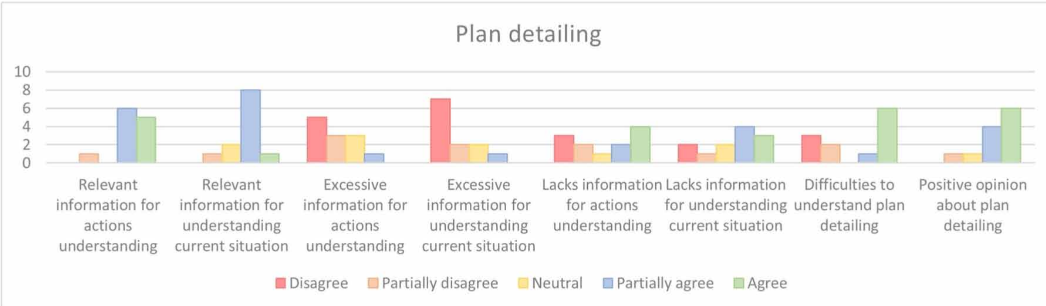
Figure 9. Results for plan presentation



Participants considered that provided information and plan detailing were relevant to understand the performed action and the response's current situation. However, they lacked other information, explaining that *"the tool presents the obstacles, but not ways of solving them"*, and reported difficulties in understanding some plan details. These results reinforce the need for training on the plan representation and indicate a need to provide additional input to monitor an ongoing phenomenon, affecting participants' analysis and decision-making (Figure 10).

Mechanisms for plan problems indication reduced the time for identifying issues and their causes, with participants thus highlighting several benefits: *"combined with the knowledge of those who monitor the plan, the information indicates possible actions to be adapted"* and *"the mechanisms help to visualize problems that the crisis team must overcome"*. However, another participant suggested to *"present a range of possible solutions for each problem"* (Figure 11).

Figure 10. Results for plan detailing



Unforeseen Situations Interpretation

System log analysis showed that the average time for diagnosis was ~8min. Also, the results expected for the comprehensive analysis and the participants' results were the same, i.e., participants judged that all unforeseen situations required further examination. Moreover, participants provided more than one solution for each disruption, and there was no disruption without a relevant solution.

The questionnaire provided extra information on the participants' perception of unforeseen situations interpretation. Provided information for unforeseen situations analysis and characterization helped to understand the current situation, with participants highlighting that such information indicated a *"need for plan adjustment"* and assisted to *"visualize problems that the crisis team must overcome"*. However, some participants lacked additional inputs for analysis, thus indicating the need to provide additional knowledge for participants to perform better analysis and decision-making in unforeseen situations (Figure 12).

Mechanisms for indicating variable inconsistencies facilitated participants' problem analysis, reduced the time to identify problems, and helped identify the problem causes. For instance, one participant mentioned that *"presenting the variables inconsistencies helps in being aware of problems"*, but other participants suggested that *"it is necessary to provide more suggestions for solving problems"*. These results reinforce the need to provide additional knowledge for analysis, decision-making, and adaptation (Figure 13).

Participants judged the mechanism for solutions provision helpful for plan adaptation, highlighting that *"the possibility of recording solutions helps the decision-making in future crises and learning"*. However, some participants reported that the tool needs *"flexibility to introduce situations during the*

Figure 11. Results for mechanisms for problems indication

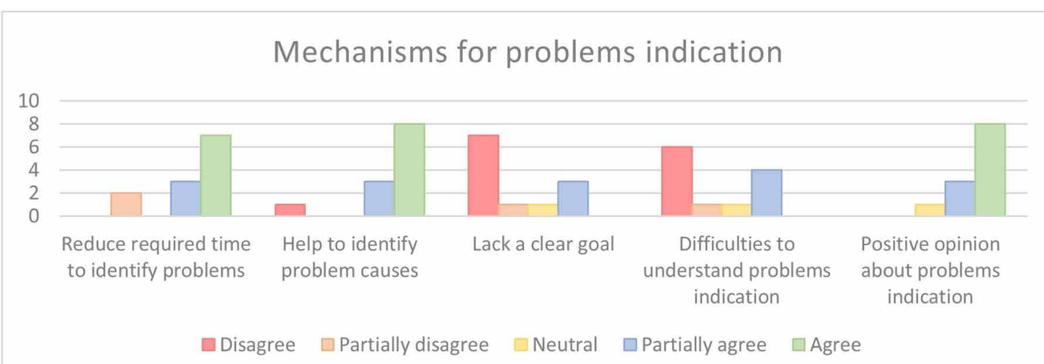


Figure 12. Results for unforeseen situation analysis

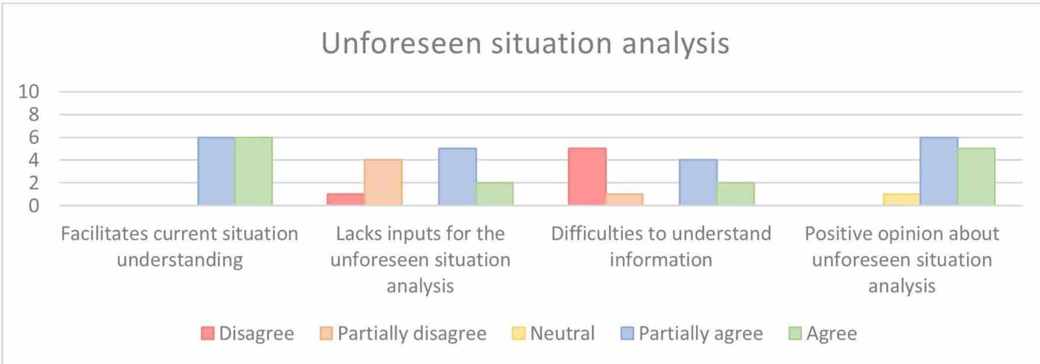
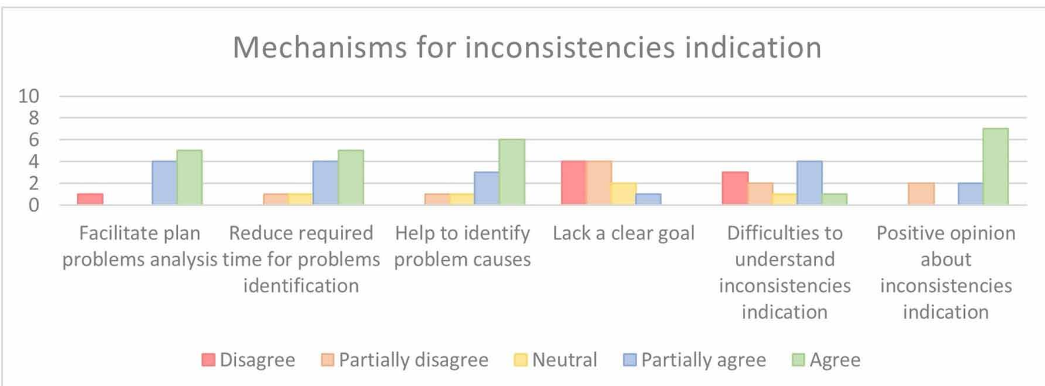


Figure 13. Results for mechanisms for inconsistencies indication



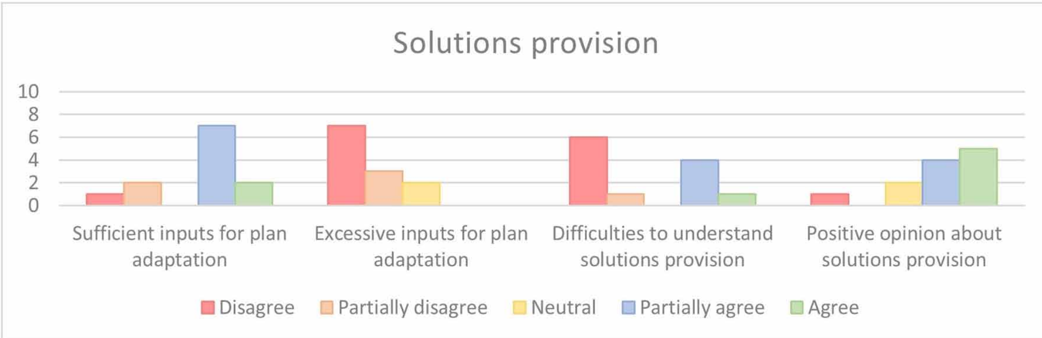
execution" and *"allow participants' feedback"*. These results indicate a need for the tool adjustment to support the plan adaptation fully (Figure 14).

Discussion

The experiments assisted in evaluating the approach effectiveness, allowing to observe how both approach and tool could support agents' duties in a domain that demands several kinds of adaptation at different stages and which aspects still need improvement. Furthermore, questions and analyses arising from these experiments lead to conclusions that can be expanded to other domains facing irregular phenomena.

The organization and availability of different types of knowledge enable teams to identify unforeseen situations, interpret their impact on recommended procedures, and make runtime adjustments. Additionally, experiments showed that experts must collaborate, share knowledge, and negotiate towards making the best decision to handle unforeseen situations because each member (a) is responsible for specific information and (b) has a different experience, which may lead to various solutions to the problems faced. Also, participants could rethink the protocols usually adopted, with evidence in phrases such as *"We need to rethink the procedures we have been adopting"*, *"We have already sent an agent to a location without the key for manual activation"*, and *"I cannot understand what is spoken over the loudspeaker, being necessary to speak slowly"*.

Figure 14. Results for solutions provision



However, the researchers also identified some challenges. The high abstraction level of plans in this domain could impact the plan reformatting to the proposed elements, make it challenging to identify unforeseen situations, and generate several plan adjustments. Interaction with domain experts was necessary, thus reducing information absence and unnecessary work. Moreover, research on the planning phase should provide tools that support a better systematization of plan development.

Participants' experience also impacts the interpretation since they may consider an unforeseen situation as demand for adjustment or something that requires no further action. This may trigger a plan adjustment when unnecessary or fail to start one when necessary. Again, a complete knowledge base provision would minimize this problem since teams can use more information to base their decision.

Besides that, plan adjustments could not be dynamically implemented due to tool limitations. Therefore, it is necessary to finish the implementation of related features so that the whole plan adjustment aspect can be tested. Moreover, we must adjust the tool interface for better visualization of state variables and all provided information simultaneously to reduce its impact on participants' analysis and decision-making.

The experiments also indicated that participants still need to understand a change in the plan representation (proposed plan elements) and more detailed training on the tool features before the experiment begins to get the best out of them.

Finally, research evaluation is another aspect of consideration. Irregular phenomena are not straightforward to simulate in a laboratory. Thus, data from real cases was gathered to design a scenario that was as close as possible to actual rainfall. Also, the researchers encountered difficulties in inviting professionals with a very particular profile for a proper approach evaluation.

CONCLUSION

Working in complex environments requires being prepared for adaptation, especially when handling irregular phenomena. Aspects such as dynamic execution, unexpected restrictions, and unpredictable decisions impose new difficulties in identifying straightforward ways to handle these phenomena. Therefore, during the plan enactment, it is common to face unforeseen situations and, as a result, to find that the plan becomes inappropriate.

The proposed approach assists the response team in facing this challenge. By comparing the plan and the observed situation, it is possible to assess whether this plan is still appropriate for handling the ongoing phenomenon or some unforeseen situation has been identified. When a disruption is reported, a plan adjustment allows devising an alternative solution to manage the phenomenon. A tool was developed to support the approach and used during experiments in the emergency management domain.

Experiment results indicated the feasibility of the proposal for handling unforeseen situations in complex environments. It provides broader support to decision-making during unforeseen situations identification, diagnosis, and treatment, besides a more structured improvisation by including information that guides the identification of alternative solutions.

Although results support the proposal's claims, some aspects still need further study. Concerning plan monitoring, the challenge is to reformat the recommended procedure to the proposed elements, thus requiring tools that support the better systematization of plan development and evolution activities. Regarding interpretation, the challenge concerns the impact of participants' experience during analysis. Hence, providing a complete prior knowledge base should assist the response team in using more information to base its decisions. Finally, as for plan adjustments, the challenge is to design a mechanism to support improvisation, i.e., a guide that allow the creation of connections between the available resources and between these resources and teams' experience, besides enabling the organization of knowledge according to the proposed elements before incorporating it into the existing plan.

For future work, new experiments aim to explore opportunities for proposal improvement, such as focusing on understanding the improvisation and solution organization aspects, besides applying the proposal in other domains. Here is important to highlight the difficulty of performing experiments in irregular phenomena due to the risks to test proposals in real phenomena (often unpredictable and life-threatening) and the challenges of a laboratory simulation (the need for data from real cases and involvement of professionals with a very particular profile). Finally, research into planning for irregular phenomena is still open. The uncertainty and lack of knowledge about the environment must be recognized from the beginning of plan development so that adaptation is no longer an ad hoc activity but something that can be, to some extent, anticipated. Hence, plans should be designed to highlight points that are more likely to be changed, thus anticipating the need for adaptation and the impact that changes will have on the plan.

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