IS Mediation of Emergency Management: Adding Prediction to the existing Framework of Activities?

Research-in-Progress

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Abstract

Fire poses a recurring threat to life and property in every society and common traditions of fire-fighting services and fire emergency management systems have developed over centuries. Such systems now comprise a repository of large datasets gathered from years of fire incidents. Motivated by the devastation caused by a recent major fire emergency in their jurisdiction, the M2inder project was initiated by a state-based fire emergency service organisation to develop a modelling tool using this and other datasets to probabilistically predict where and when fires are likely to occur. The contribution of study presents the findings from a participatory action research (PAR) study of the M2inder project when a team of both practitioners and researchers with varying expertise, was assembled to guide the development of the M2inder system.

Keywords: Information Systems, Risk Management, Disaster Management, PPRR, Activity Theory, Firefighting, Participatory Action Research, pattern recognition

Introduction

Unanticipated natural and manmade disasters produce global social, environmental and economic impacts. Preventing or at least minimising such impacts should be considered among the grand challenges engaging information systems (IS) scholars (Winter and Butler 2011). In economic terms, it is estimated that between 2000 and 2012, over 1.5 billion people worldwide were affected by disasters with a total economic loss of over US$1.3 trillion (Aitsi-Selmi et al. 2015). The social and environmental impacts are more difficult to measure but are the focus of substantial research into community preparedness, response and resilience (Kapucu 2008). In the Australian State of New South Wales (NSW), Fire & Rescue NSW (FRNSW) is the agency responsible for minimising the impact of urban fire hazards and emergency incidents on people, the environment and economy. In 2016/2017 FRNSW responded to 123,711 incidents, of which 21,784 were structure fire related (FRNSW 2017). It is estimated the economic impact of these incidents exceeds US$122 million (Productivity Commission 2018).

The practical agenda of the *M2inder* project is to produce an analysis tool using historical data and datasets to predict with a reasonable level of reliability in advance (up to seven days), the times, regions or localities of structure fire hazards enabling substantial innovation in firefighting strategies and techniques through the ability to predict. The research objective will contribute to the academic literature via (1) IS in emergency management; (2) data mining, analysis and modelling involving multiple large data sets collected for other purposes in order to provide decision support in future events;

and (3) adding to IS theory by making a contribution to the established PPRR (i.e. Planning, Prevention, Response, Recovery) framework of emergency management to include prediction, rather than just response. Due to the focus on IS supported action, the Cultural Historical Activity Theory (CHAT) (Vygotsky 1978; Leontiev 1981; Engeström 1987) was used as an instrumental theory providing an explanation of the phenomenon of interest in order to improve understanding of the problem (Davison et al. 2012). Consequently, we pose the following research questions:

1. Can the occurrence of a (structural) fire be predicted in advance?
2. How can underlying IS theory and expertise contribute to the development of a fire prediction tool?
3. What are the implications of such capability for the Comprehensive Emergency Management framework?

This paper is organised as follows: first, we review the literature on IS issues in emergency management in order to establish the context for the study and identify the research gap(s). Next, we describe the background to the *M2inder* project describing an actual case of a community lost to fire which motivated the project. Third, we present the research approach, design and justification for the Participatory Action Research (PAR) methodology. Fourth, we present our findings through the lens of Activity Theory, and analyse patterns generated by *M2inder* from years of data; and finally, we examine the activity of the project as a whole.

Literature Review

Although CHAT is commonly known simply as Activity Theory in IS research, its cultural-historical tradition (Vygotsky 1978) is acknowledged in this research. Indeed, in their use of Activity Theory in a post-analysis study of emergency management, Chen et al. (2013) recommends the addition of environment/context and timeline as elements to those of the Engeström (1987) framework of activity theory commonly used in IS studies. The first two sections of this literature review set the cultural-historical context for our research in preparation for the third section which subsequently presents literature supporting the CHAT analysis of the findings. Edwards et al. (2017) notes a fragmented body of knowledge and a lack of academic peer reviewed literature within fire and emergency management domain which is supported by the findings from Jennings (1999, 2013).

IS and Disaster Management Research

In the wider context of this paper, a significant contribution of IS scholars has followed the seminal work of Simon (1960) dealing with the challenge of collecting data and processing it into information, on which important decisions can be based (e.g. the analysis of decision support systems by Shim et al. 2002). More recently emphasis has been placed on intelligence, analytics and big data (see e.g. Chen et al. 2012; Shollo and Galliers 2016). As articulated by Clarke (2016 p. 2) "the moderate enthusiasm engendered by 'data warehousing' and 'data mining' in the 1990s has been replaced by unbridled euphoria about 'big data' and 'data analytics'".

With respect to the use of IS for emergency management, the compilation by van de Walle et al. (2014) provides a comprehensive overview. In addition, here is an abundance of reports where IT is used in emergency management, but this is mainly at the practitioner level where researchers aid practitioners to study aspects of emergency incidents, such as "fire service response times" (Challands 2010). However, only a small body of IS academic literature focusses on the use of IS in the field of firefighting (Revelle 1989, 1995; Badri 1998; Rosenberg 2000; Yang et al. 2006; Rohde 2010). Mathematical modelling using population data (Rohde 2010); and the use of neural network regressions (Yang et al. 2006), represent an even smaller volume of literature presenting predictive capabilities and investigation of the application to practice, compared to the study presented here.

Of some relevance to our research demonstrating that IS can contribute to practical outcomes for emergency management, has been work on community warning (Bunker et al. 2009, 2010) location and dispatching of emergency services (Revelle 1989, 1995; Badri 1998; Han et al. 2000; Gendreau 2001); analysis of the emergency response (Chen et al. 2008, 2013); the interoperability between emergency service agencies (Allen et al. 2014); modelling socio-economic factors (FEMA 1997; Chhetri 2010; Ceyhan 2013); and using geographical IS (GIS) for emergency management (Cova 1999).

In the realm of prediction, we note that weather forecasters have a long history involving statistical analysis for prediction (Lorenz 1956; Lorenc 1986; Rosenberg 1999) having been used in areas such as building energy management (Lazos 2015), are related in concept to our study. Risk Management is also predictive in nature (Saunders et al. 2006; Powers 2008) and incorporates emergency management (Pearce 2003; O'Brien et al. 2006). Predictive analytics have been used for new and novel ways to transform supply chain design (Waller and Fawcett 2013), the tides (Godin and Taylor 1973), analyse social media trends (Lu et al. 2014), and for data analysis (Wamba et al. 2015).

The literature shows the potential of IS to contribute significantly to the field of emergency management with technology, communications, data processing capability and decision support. However, there is still much to learn in the area where (1) large datasets come from different emergency service agencies using differing standards and data properties (types and units) as well as from other sources such as weather bureaus and population records; and (2) the focus is on prediction for future action rather than retrospective analysis. Our study acknowledges the risks and challenges of big data analytics, appreciating the examination by Clarke (2016) using examples of projects involving "re-purposing data, consolidating data from multiple sources, applying analytical tools to the resulting collections, drawing inferences, and acting on them" (Clarke 2016 p. 1). Clarke (2016) describes the range of technical and human factors influencing the quality of both the data and the information produced from them, observing that the quality of the information can only be properly assessed once generated and used.

Adding Prediction to the Comprehensive Emergency Management Framework

As stated previously, the objective of the research is to investigate the feasibility and efficacy of using big data analytics and modelling tools to mediate the activity of prediction. Also, this activity as a fifth core element of the Comprehensive Emergency Management framework (1979) currently uses the core elements of Prevention, Preparation, Response and Recovery (PPRR) summarised as follows (Edwards et al. 2017):

1. **Prevention/Mitigation** activities eliminate or reduce the probability of occurrence of a disaster. Examples include legislation, modifications to the built environment, and planning.
2. **Preparedness** activities extend mitigation activities but cannot prevent the occurrence. Examples include warnings, training, stockpiling and pre-deployment of resources.
3. **Response** activities occur in parallel as the disaster impacts. Examples include first response, medical care, shelter, feeding and search, and rescue.
4. **Recovery** activities aim to return an impacted area to the same or better circumstances than before the disaster impacted over the short, medium and long term. Examples include accommodation, clean up, loans, planning, and redevelopment.

A review of relevant literature above highlights the complexities and context of the project with multiple stakeholders, numerous sources of data and diverse requirements as well the challenges of ensuring quality in big data analytics, facilitating interoperability between agencies and enabling disruption of the entrenched PPRR comprehensive emergency management framework. The research agenda required a theoretical lens encompassing these complexities in a holistic, yet pragmatic way practitioners would understand. The researchers on the *M2inder* team suggested cultural-historical activity theory (CHAT) which was confirmed when the practitioners readily appreciated its language and concepts as will be discussed later in the paper.

CHAT as an Instrumental Theory

CHAT, also known just as Activity Theory, has gained the attention of IS researchers who find it suitable for analysing the design, development and evaluation of ICT-based systems as well as for computer-supported activities of groups or organisations (see e.g. Kuutti and Vikkunen 1995; Korpela et al. 2000; Hasan and Gould 2001; Hasan and Pfaff 2012; Chen et al. 2013; Waycott et al. 2014). While the Engeström Activity System (i.e. Figure 2) is commonly the basis of this analysis, other more insightful aspects of the theory are frequently overlooked, in particular those that could address the complexities and dynamics of socio-technical systems (Kuutti 1996). While generally supporting Engeström's model, Blackler (1993) observes it assumes some level of agreement will exist in a community of practitioners on the object of their shared activity. In the case of complex organisations this may not be the case and there are likely to be a plurality of divergent interest groups favouring a range of goals and priorities.

In our study we draw on the rich cultural-historical tradition which emphasises the context of activities under investigation and regards relationships within and between activities as dynamic and often dialectic (Hasan et al. 2016). CHAT takes a holistic perspective placing activity above action and operation (Leontiev 1981) and is particularly relevant in situations possessing a complex context where participants, their purposes and tools are in a process of rapid and constant change (Hashim and Jones 2007). A basic premise of CHAT is that "activity is primary, that doing precedes thinking, that goals, images, cognitive models, intentions, and abstract notions like 'definition' and 'determinant' grow out of people doing things" (Morf and Weber 2000 p. 81). It thus has the pragmatic perspective that appeals to practitioners in our study.

As depicted in the Engeström Activity System, at the core of an *activity* is the relationship between the subject (i.e. doer) and object (i.e. what they are doing and why) (Allen et al. 2013; Hasan and Kazlauskas 2014). The relationship is dialectic in the sense that its subjective and objective natures are inseparable (Kaptelinen 2005). The object of activity encapsulates its purpose and no human activity is without an object or purpose i.e. something undertaken with its own particular purpose is able to define an activity (Kaptelinen 2005). Human activity is distinguished by the fact that it is mediated by physical and psychological tools (Vygotsky 1978). Leontiev (1981) distinguished between long-term *activities* to be understood in terms of the subject's motive and purpose within a cultural-historical context, be distinguished from short-term goal-oriented *actions,* meaningful only in terms of the motive, purpose and context of the activity of which they are an element.

A unit of analysis is the most basic element of a scientific research project (Long 2004). It is the focus of study about which an analyst may generalize (Long 2004) or use to build theory (Hasan and Banna 2010). In social science research, typical units of analysis include individuals (i.e. most common), groups, social organisations and social artefacts.

Research Methodology and Design

As discussed, this research involves a study of the *M2inder* project which aims to develop data modelling tools predicting the likely time and place of fire incidents seven days in advance, thus improving the efficacy of firefighting. The research questions ask how this can be done, how IS expertise could contribute to this effort and how predictive capability would change the existing PPRR framework (i.e. our focal theory) for emergency management. The motivation described above, provides evidence for the complex, dynamic and disruptive context of the project with multiple stakeholders, sources of data and diverse activities. It underpins our choice of Activity Theory as our instrumental theory and *tool-mediated activity* as our unit of analysis. We have described attributes of CHAT guiding the analysis.

Research Approach

With regard to an appropriate research approach, both design science and action research were considered: the former because an innovation IS artefact was being created, the latter because a team including both practitioners and IS researchers was established to oversee the project. Following discussions with the whole *M2inder* team about the potential of practitioners and researchers to provide complementary skills to the project, the latter approach was selected. Action research allows inquiry, and explaining social situations through informed interventions, "it is problem-focused, context specific and future-orientated" (Waterman et al. 2001, p. 4).

Action Research (Baskerville 1999) develops a solution to a practical problem of value to the people with whom the researchers are working, while concurrently developing theoretical knowledge of value to a research community (Kock et al. 1997; Coghlan 2001). The dual outcome perspective means the research is embedded within a practical context that is explained and changed with improved practical outcomes and new insights that emerge (Chaisson et al. 2008).

The PAR method adopted during the project included 240 structured and unstructured interactions were undertaken with research institutions, technology suppliers, project and management teams that included multiple cycles of diagnosis, action planning, intervention, evaluation and reflection (Edwards 2017).

The PAR Diagnosis

The motivation for the *M2inder* project arose from the devastation that occurred in the Blue Mountains some 80km west of the NSW state capital Sydney on 17th October 2013. The fires, burning on three fronts, were the worst natural disaster in Blue Mountains history and led the NSW government to declare a state of emergency. Some 196 homes were destroyed with significant damage sustained by 132 more. Intense fires further tore across south-eastern Australia in ferocious wind conditions and high temperatures, darkening Sydney's skies with smoke and ash. Temperatures hit the mid-30s centigrade with wind gusts reaching 90kph throughout the day (Koperberg 2014). Based on information available at the start of the day, the eventual devastation was unanticipated. Total fire bans were put in place as a precautionary measure across the greater Sydney metropolitan basin when temperatures of approximately 33 degrees Celsius were forecast. This forecast caused emergency managers to be alert to the potential of fires occurring but not alarmed at an impendent disaster. We chose to view these events of the day through an IS systems 'lens'.

It was the shocking events of this day that started the Chief Information Officer (CIO) of FRNSW thinking about how information systems could be used to reduce the devastation of such events. He speculated to our participant researcher that large sets of data he knew to be available, could be analysed and modelled to forecast with high probability where and when fires were likely to occur. Such information could be used by emergency and emergency managers to pre-deploy resources in the appropriate location at an optimal time to stop or reduce the impact of a fire. In the case of the October 17th emergency, he estimated if a fire appliance had been deployed to centre of the town it would have observed the smoke caused from the ignition of the fire and been able to travel to and extinguish it before the fire spread to the rest of the town.

The top section of Figure 1 shows the level of risk existing at 8am for Lithgow and Winmalee (i.e. two towns in the Blue Mountains, about 60km north west of Sydney, New South Wales). Both were in the low to mid-level range of the spectrum with orange dots dominating the map. The western area on the left represents the risk to properties in the community of Lithgow, near which a fire front had been burning overnight. Winmalee (i.e. top right) is 80kms by road to the east and located in the area in where most properties were destroyed or damaged later in the day. With the fire burning near Lithgow at 8am, there was no indication from observations on the day any of the properties at the right (i.e. eastern) end of Figure 1 near Winmalee were at any great risk. While Lithgow received minimal damage, by the end of the day Winmalee was devastated.

The bottom section of Figure 1 shows outputs of the modelling starting at 1:27pm when the fire reached the Winmalee area. This clearly shows the modelling estimated a higher level of risk (i.e. a greater proportion of red dots) to properties at Winmalee. By 2:15pm that afternoon the majority of houses designated as high risk in this model were destroyed or damaged. Much of this could have been avoided if the information in Figure 4, produced retrospectively from an analysis of property and weather data recorded on the day, was available in this form at the time.

The CIO of FRNSW was excited by the possibility that if higher risk areas could be predicted ahead of time, then better outcomes can occur than is currently the case. He speculated that if a single fire appliance had been located in the centre of the township of Winmalee, it would have observed the ignition of the fire and would have been able to extinguish the fire before causing such disruption and damage to people and property. With a predictive tool, emergency services manager(s) could have made a more informed decision on where and when to pre-deploy resources. The decision to proceed with the *M2inder* project was made in November 2013 with the objective to enhance the ability of FRNSW to save lives and property by predicting where and when fires start. This decision reflected the belief of FRNSW management that fire prediction was possible using information systems with data analytics and modelling capability, thus providing a positive answer to research question 1 (i.e. can the occurrence of a fire be predicted in advance?). The action research approach to studying this project, aimed at answering the remaining two research questions, is now described.

Sources of Data for M2inder

The initially available data from FRNSW on past fire incidents and responses, was very extensive covering 22 years of electronic data collection stored in two main databases across a large number of tables. However, with most case studies the data wasn't collected for the purpose of developing patterns and predictions. Instead the data was collected for operational planning, financial, human resources, occupational health and safety (OH&S) and basic statistical purposes. At the outset, full access was provided to 22 years of structural fire data across the state of NSW. However due to certain data quality issues, the data range was limited to the most recent eight years. We were granted access to documents relating combating structural fires including government policy documents, information strategies, operational reports and risk profiles and staff.

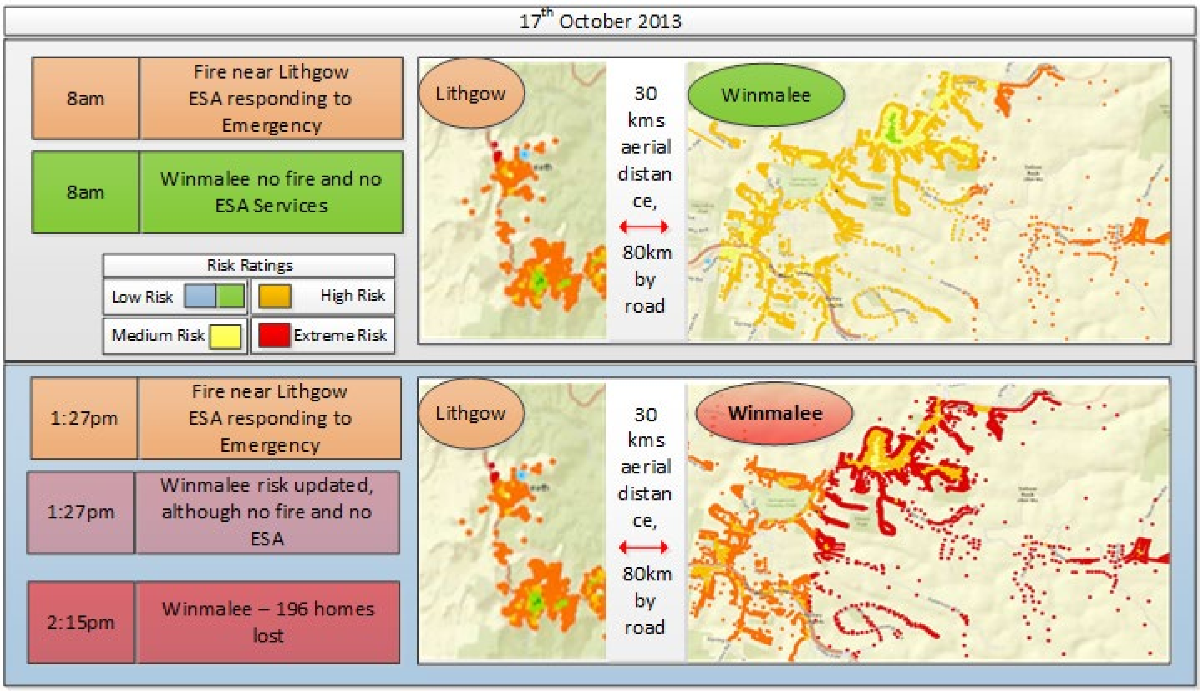

Figure 1 – Weather and Property Data from the October 17th, 2013 Blue Mountains fire emergency retrospective risk

Analytics and Modelling

Guided by external experts, models were constructed, and data sourced and analysed through multiple lenses. The complexity of the problem was enormous, and the project team cycled through repeated Planning and Intervention Stages of PAR to explore different ways of analysing and modelling the data. We choose seven days as the forecast benchmark based on interviews with meteorological staff from private and government agencies. We believe that weather is a key factor to human behaviour which influences both the likelihood and consequence of a structural fire occurring. Access to accurate (i.e. although sometimes divergent) weather models is a key component of the *M2inder* project (Meteye 2015). For several months no solution presented itself. Initial results from vendors and consultants did not yield any trends and they concluded there were no patterns in the data. Different analysis techniques were undertaken by the project team to search for patterns in the data. The project team was cognisant it could 'see' a pattern without it actually existing, so check points were always placed in project meetings to challenge findings.

The breakthrough came when the two author participants observed temperature patterns during a presentation. These patterns were not recognisable in the consultants' analysis but did align with statements from previous discussions with firefighters and emergency managers. The modelling demonstrated a trend to increased fire incidents on days with cold mornings (e.g. 7C to 16C) coupled with very low increases in temperatures of 4C to 8C. This trend was obscure, and a decision was made to start again and focus on datasets (i.e. previously described) that could be used as inputs to a forecasting system (i.e. *M2inder*). Broken down into three basic components, these included socio-economic data, weather forecasts and previous structural fire history. The project team extracted, merged and cleaned data from the operational databases and combined this with weather data. Preliminary analysis highlighted patterns aligned to observations of fires occurring on cold days.

Discussion: The PAR Reflection Stage

In answer to our first research question in the exploratory phase, reported in the motivation section of the paper, we demonstrated the possibility of forecasting the occurrence of a fire in advance through data analytics and modelling. The exploratory exercise with a vendor who modelled the weather and demographics data of the day of devastation in the Blue Mountains, provided evidence that the fires could have been predicted. In answer to our second research questions we have shown how IS expertise has driven data analysis with further modelling in the *M2inder* system resulting in more general predictive fire patterns by time and location. With weather predictions routinely available for up to seven days (i.e. and covering 400m2), the *M2inder* system could when fully functional, alert fire and emergency agencies and warn residents. The *M2inder* system represents a significant advancement in emergency management and fire fighting in particular.

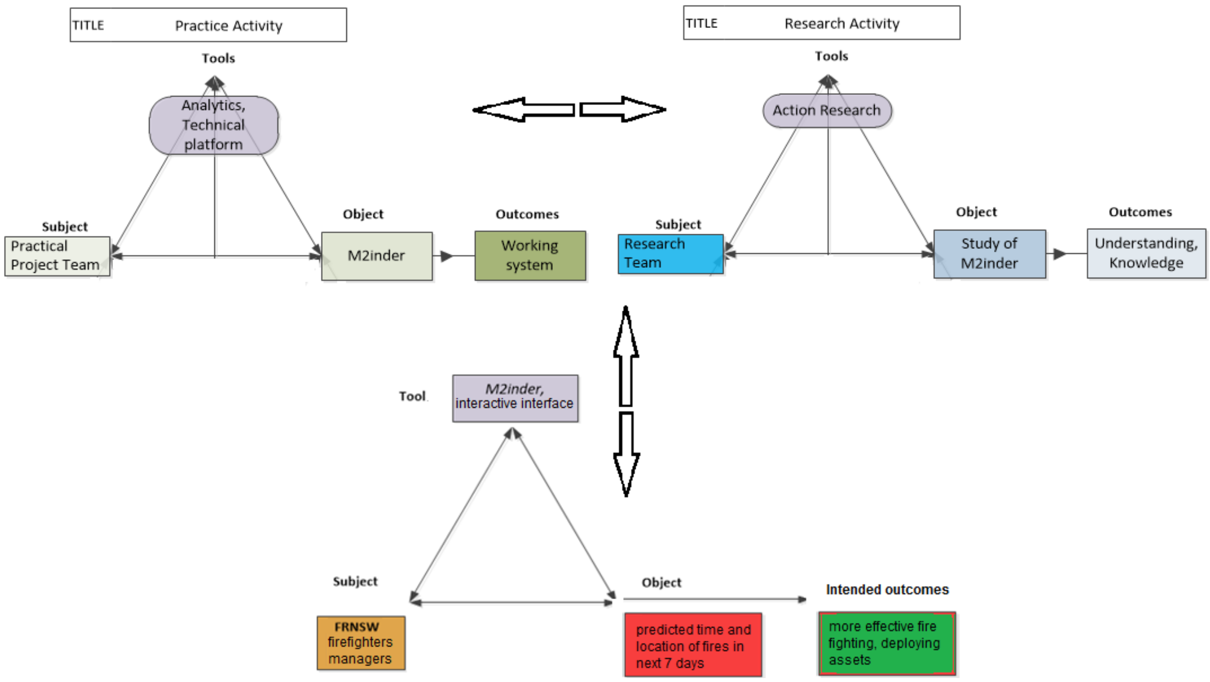

Figure 2. The synthesis between the activities of use, practice and research in the *M2inder* project

To address the second research question, we now discuss how the *M2inder* tool provides the potential to fundamentally change traditional emergency management practices. The original Comprehensive Emergency Management framework is widely accepted and has been the basis of FRNSW practice for many decades. Figure 3 illustrates the traditional process flows between the Response, Recovery, Prevention and Preparation activities. Our research has portrayed how the innovative activity of prediction is only now becoming possible through modern IS systems with data analytics and sophisticated modelling of the CHAT activity. The researchers on the *M2inder* team who performed the analysis, viewed prediction as additional to traditional PPRR activities. Our modified Comprehensive Emergency Management framework on the left of Figure 2, highlights the addition of prediction to the PPRR Framework. However, the practitioners on the team while impressed by the *M2inder* tool argued that it was really another new element of the preparation activity and preferred more modest change. In this paper we have updated the Comprehensive Emergency Management framework to include prediction - an activity ideally considered as part of an all hazards approach.

The original Comprehensive Emergency Management framework illustrates the data flows between Response, Recovery, Prevention and Preparation activities. Our modified Comprehensive Emergency Management framework (i.e. Figure 3) shows the additional data flows between PPRR and now including Prevention and a 2-way link (e.g. purple arrow) to inform the practical and research activities. It is envisaged that this is how the *M2inder* platform will analyse data. Its output will provide advanced insight to disaster and emergency managers to avert potential loss of life and property. The model developed in the case study confirmed our speculation that fires could be forecast. Although discrepancies in the PPRR framework and the results of the data analysis identified that an additional prediction component is included in the current framework. We propose the Comprehensive Emergency Management framework should include a predictive component tailor to forecast relevant hazards. In this case we have examined structure fires, but it is our intention to expand the framework as it is developed to encompass an all hazards approach across the entire man-made and natural disaster spectrum.

Generalisability of this research comes from the significance of an exemplar case for research into IS support for state-led predictive programs, as NSW is one of the largest states in the world by size and population. With its vulnerability to wild-fire, floods and drought, disaster management is a major concern. The New South Wales police force, fire department and agencies such as education and health, have comparable responsibilities with any of the major states in the developed world. With input from Federal Government, NSW is coordinating with other Australian states on emergency management programs exchanging information and lessons learnt. The findings from this research have broad practical application to many other state governments in Australia and other comparable countries. We also make the claim that there is a measure of generalisability although not necessarily replicability, due to significance of the case and the abstraction of concepts when applying the Activity Theory model which made sense to both researchers and practitioners. We adopted participatory action research as a method and language of activity theory to manage the development process, keeping the team and vendors on track.

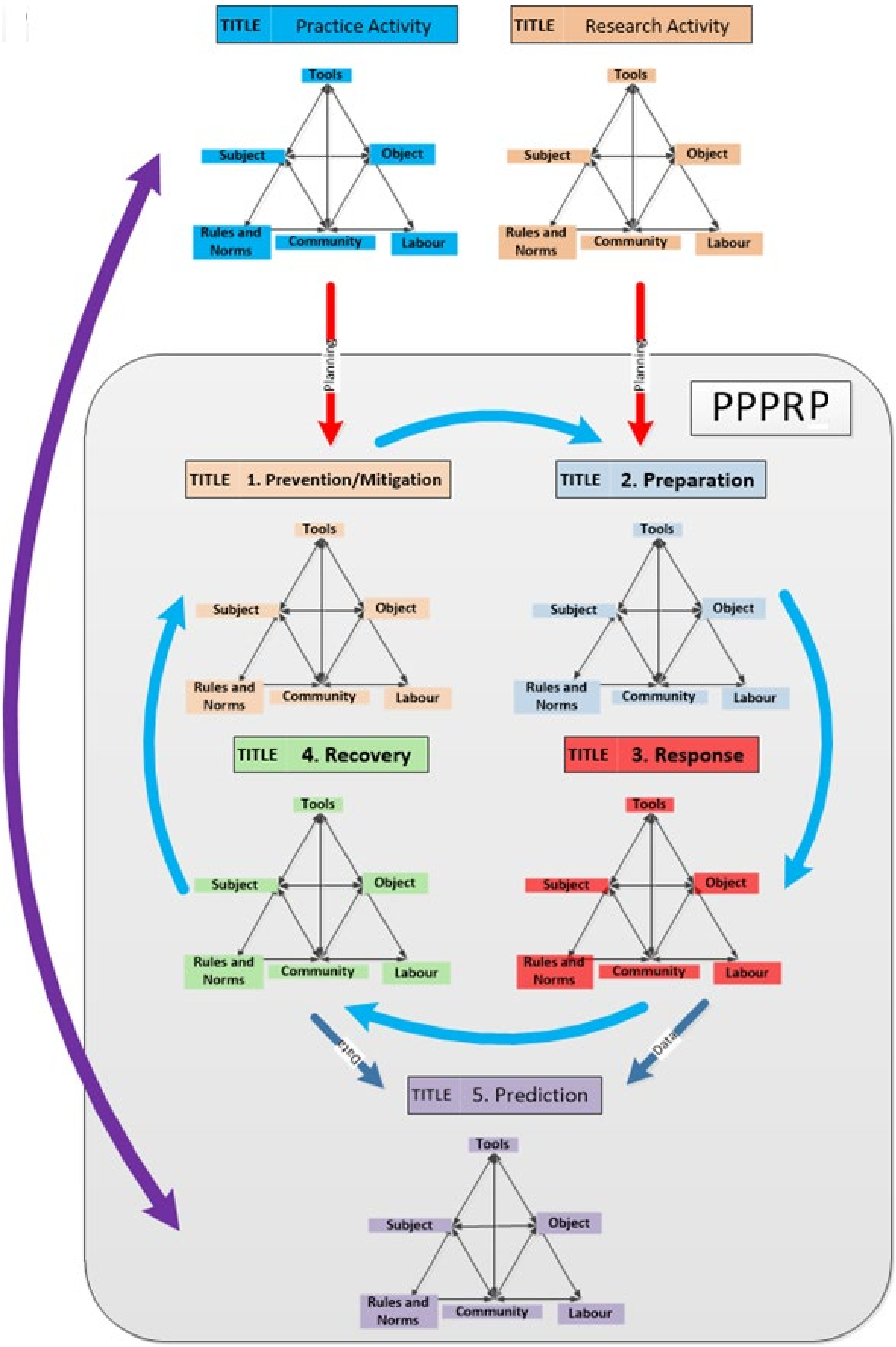

Figure 3 Holistic AT view of the *M2inder* Prediction activity added to the PPRR Framework to become PPRRP (i.e. showing data and information flows)

Conclusion

Innovative yet resourceful information systems, are needed to meaningfully disentangle the vast quantities of data collected over several years to address several issues (i.e. including cultural, community, political, industrial, financial and legislative) to forecast the regions, areas, localities or properties with the highest likelihood of a fire occurring. In this paper we reviewed the literature and identified a gap in the application of data analysis as a tool to forecast the likelihood of structure fire emergencies. We proposed that our project, undertaken in partnership with FRNSW, discovered patterns that can lead to the development of the *M2inder* model. It is envisaged that *M2inder* will use a wide variety of data sources to more accurately predict the fire risk of building structures into the future.

Our contribution is to use the IS theory coupled with Participatory Action Research to engage with a multitude of local and international technology suppliers and universities to consider whether emergencies could be forecast. Concurrently we use Activity Theory as the lens to consider how the *M2inder* model would operate within the comprehensive Emergency Management framework and identify how it would operate through an extension of the framework.

This research widens the scope of emergency management to included prediction as an additional area of responsibility for IS scholars. We suggest this perspective is essential for a realistic approach to emergency management and prevention. Our case leads us to speculate that local weather conditions are at least one of the key factors in determining the risk of a structure fire occurring. We propose to extend this speculation to include other datasets which can be included to formulate dynamic risk models. These would include demographics, socio economic status, census data, geospatial information, past response history and lessons learned which will form the future basis of the data analysis *M2inder* framework.

Our research to date leads us to postulate that in Sydney, urban fire agencies need to be on a higher level of alert for structural fires on days where the weather forecast for low temperatures in the morning, with no significant rise in temperature over the course of the day. An extension of this would be to implement a plan to embed the prediction process into FRNSW to support decision-making a week in advance on resource requirements, utilisation and pre-deployment when and where fire is predicted. This combined with a proactive education and engagement program with at risk communities, may lead to reductions in the impact of structure fires.

The outcomes of this paper are relevant to the IS community, practitioners and emergency service agencies and will be of interest in endeavouring to reduce loss of lives and property resulting from structural fires. Lessons learnt for and hopefully from this paper, will have implication beyond NSW and the firefighting community as it represents reinventing data in a new direction of research. Most significantly the research presented here enables us to demonstrate that IS expertise can contribute to an understanding of the problem in detailed fire prediction. This research conceptualises the complexity of information systems required to manage trans-disciplinary teams facing the task of forecasting future disasters. The challenge to governments and emergency service agencies is in translating the increasing trends of emergency management whilst finding practical solutions using existing science and managing gaps in complex data (Aitsi-Selmi et al. 2015). The system proposed will analyse low prevalence fires although common numerically, which are rare occurrences across a city. In this paper, we investigate the issue of fire forecasting by focusing on the analysis of data for events up to seven days in advance and changing the paradigm on firefighting using new data to change the direction and design of firefighting techniques practices while investigating influences on organisational cultures and norms across emergency service agencies.

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