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Disaster Knowledge Management Analysis Framework Utilizing Agent-Based Models: Design Science Research Approach

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Abstract

Disaster Management (DM) knowledge has long been acknowledged as playing a significant role in reducing the impact caused by disasters. It helps people at the decision-making level to produce contextual decisions, as they are produced from the interaction of the involved social entities and their experiences and those who are on the ground to appropriately react towards the disaster. While it is seen as critical the DM activities, its adoption is still challenging due to its complex structure and availability. This paper employs the Design Science Research (DSR) methodology in Information System (IS) research to develop and validate a knowledge transfer analysis framework to unify access to semi-structured DISPLANs (Disaster Management Plans) through a unified repository. In the development, Agent-Based Models (ABMs) are used to code the DISPLANs to enable their transfer into a repository. The Meta Object Facility (MOF) Metamodeling Framework is then used to create a repository that is ready for storing the content of ABMs. This developed framework is then validated using a real case study of the flood DISPLAN of the State Emergency Service (SES) the State of Victoria, Australia. At the end, this paper contributes to: (1) a validated knowledge transfer analysis framework supporting DM resilience endeavors; (2) demonstrate the DSR methodology as a frame for IS research.

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1. Introduction

Currently, the agency leading the program to combat the disaster assumes the role of organizing and eliciting the knowledge, and ultimately structuring it in a shareable and reusable format. The knowledge is produced as Disaster Management Plans (DISPLANs). However, accessing the knowledge specified in a semi-structured natural language format is very challenging. The written knowledge tends to be structured in a business specification format which, in fact, is seen as subjective by the stakeholders. Much analysis may be required to enable development of useful and actionable insights. In this paper, we view the challenge of DM as one of harnessing and sharing knowledge between stakeholders who are involved in the timely and effective reduction of the impact of a disaster. The first step towards this is to revisit the codification of DM knowledge document sources to facilitate the reuse and sharing of the knowledge they contain. But analyzing the written knowledge in a complex domain, such as DM, is not only difficult but also time-consuming [1]. With all its prominence in DM activity, Prevention, Preparedness, Response and Recovery (PPRR) does not actually conceptualize the process of DM knowledge holistically, rather it does it sequentially [2]. This feature of PPRR is completely inconsistent with the modern view of aiming to have risk management permeate all DM activities.

It is well accepted that software practitioners typically engage in iterative thinking and problem-solving, moving up and down multiple abstraction layers. Linear and sequential descriptions of events are inherently limited. Participants are hindered from engaging beyond the limit of the event timeline. In order to mitigate the risk of introducing errors, sequential modelling was abandoned in the software development many years ago [3]. Applying this same paradigm and insights to representing disaster management processes, a multi-layered metamodeling approach which follows the Meta Object Facility (MOF) approach [4] is proposed. As a first knowledge analysis step to enable this, the paper proposes an approach based on Agent-Oriented Analysis (AOA) to appropriately codify DM knowledge.

Drawing from the emerging DSR methodology in IS [5], this paper contributes to this field by introducing a knowledge transfer analysis framework. This is a framework in which the DM knowledge is analyzed prior to transfer. The aim is that the complex characteristic of the knowledge can be disentangled and subsequently transferred into a representative repository, facilitating sharing and reusing activities. In addition, this paper demonstrates that the knowledge deposited in the repository can be the foundation of a comprehensive and holistic decision making mechanism in disaster events. This due to the fact that Agent-Based Models (ABMs) are capable to parse the complex characteristics in the DM that are inherently existed hampering the affective and efficient activity. The DSR frames the research activities to rigorously develop and validate the framework through proof of concept, proof of use and proof of value [6]. To the end, the developed and validated framework facilitate a better knowledge representation in the repository that can contribute to the DM resilience endeavors.

The essay proceeds as follows: The following section provides related works from the extant literature of the study. Section 3 discusses the methodology underpins this research. Section 4 illustrates the development of the artefact. Section 5 elaborates the evaluation strategy of the developed artefact. Section 6 presents the discussion and this research is concluded by Section 7.

2. Related Works

The DM knowledge has four characteristics in common with ABMs: a) *Situatedness* in an environment [7]. As disasters are dynamic, unpredictable and uncertain, the environment changes rapidly which leads to the second characteristic. b) *Time sensitivity* [8]; in a disaster, every activity has to deal with deadlines, otherwise the consequences might lead to casualties, or even fatalities. c) *Non-deterministic* [9]. Disasters often throw up unexpected eventualities. This factor means the level of unpredictability is very high. d) *Presence of autonomous entities* [10]. This means that in a DM activity, individuals/agencies/organizations are coming from different backgrounds, knowledge, abilities, structure, mandate, with no common perception and so on. The agent-based modelling approach enables analysis of complex systems, in particular socio-technical systems.

Various researches have been undertaken in an attempt to structure the DM knowledge to be better understood [11-13]. Of all these, one of the most notable is described by Othman *et al.* [11]. In their work, they do not only prescribe how the knowledge is structured addressing the knowledge layers from conceptual to planning to the real world. They also go beyond that by describing a proof-of-concept through developing a sophisticated architecture to allow the DM knowledge to be deposited in a metamodel-based repository [14]. The objective of their research is enabling the structured knowledge to subsequently be stored for sharing and reusing purposes by others in the typical DM activities. In the knowledge structuring processes, they employ the Meta-Object Facility (MOF) framework developed by OMG in Software Engineering (SE) domain [11].

The adopting of MOF for decomposing the knowledge structure complexities can also be observed in other studies [13, 15]. These scholars successfully demonstrate that the knowledge is structured to be identified in the planning/policy (*M1*) – real-world (*M0*) layers which subsequently facilitates them being transferred into the metamodel-based repository (*M2*). In this regards, the metamodeling MOF is a common technique to define the abstract syntax and interrelationship semantics of models [16]. In the context of knowledge transfer mechanism, employing the MOF as the framework to regulate the process is defined by OMG [4]. However, the metamodel-repository in Othman and Beydoun [17] fits for both natural and man-made disasters and for all DM phases, while with others, their metamodel repositories are only for a particular phase where the fuzziness and incompleteness still exist. In addition, the DM knowledge structure deposited in the repository

In this thesis, knowledge from the *M0* layer is analyzed and structured in *M1*. Subsequently it will be transferred into the *M2*, the metamodel layer. To enable this process, a set of relationships must be defined between elements of source and target models. It requires an understanding of the model in the abstraction level to be able to develop a clear sense for this particular task. The challenges in the first place are all the complex characteristics across the DM knowledge in the DISPLAN that need to be analyzed and modelled. This is essentially aimed at extracting all those complexities and at the same time preparing them for a depositing process into the repository. Therefore, on the other hand, a representative repository which can cope with all those complexities should also be prepared to allow the transferring process. Once the model and repository are in place, the transfer process can be prepared.

3. Methodology

DSR has been the emerging paradigm in IS research [18]. This is not only because its main concern is not to test nor develop a new theory as has been the common practice in IS communities, rather it is problem-solving oriented. In other words, the objective is to create a new IS artefact for solving ubiquitous complex issues [19]. In our context, it aims to develop a framework facilitating knowledge codification of the DISPLAN and subsequently enabling transferring it into a repository. The DSR framework comprises 7 (seven) activities as shown in Table 1. Each of them is described in the context of guiding the activities in this research.

Table 1. DSR methodology for developing and evaluating the knowledge analysis framework.

No.	Section	Content
1	Introduction	This study aims to produce a framework facilitating codification semi-structured knowledge out of the DISPLAN and subsequently transferring it into a representative repository. The objective of the framework is to contribute the DM resilience endeavors. The ABMs, the MOF metamodel and the knowledge transfer and representation challenges are introduced.
2	Literature review	Reviewing the key concepts of the framework: the ABMs, the metamodel, the knowledge transfer, the MOF adopting to frame the transfer process in the existing and related works. This section also presents the challenges in the context of this research.
3	Method	DSR is employed as a research methodology to build and evaluate the artefact: the knowledge analysis framework.
4	Artefact description	Descripting on (1) how the ABMs are used to portray the knowledge out of the DISPLAN; (2) how a representative DMM-based repository is prepared by annotating it; (3) how the MOF is used to frame the knowledge transfer processes of ABMs and the annotated DMM-based repository.
5	Evaluation	A real case study of SES State of Victoria, Australia is used to evaluate the effectivity and efficacy of developed framework. A DM expert from the SES Victoria is engaged to examine the evaluation processes.
6	Discussion	Discussing as to how the developed framework addresses the research objective.
7	Conclusions	Concluding whether the knowledge analysis framework developed presents the contribution (knowledge and practical) to the DM resilience endeavors.

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Hevner et al. [20] have laid a foundation of a concise framework upon how the DSR is undertaken in the IS, in terms of contributing and producing rigorous IS artefacts, namely: model, method, construct and instantiation. In this research, we employ DSR framework of Gregor and Hevner [6] to frame the research activities. Each of the DSR activities is discussed as each section in this paper. This is due to objective of the paper to show how to rigorously develop and evaluate an IS process and product embracing the DSR methodology. Thus, each step of the DSR boils down as each section in the context of research activities in this paper. The first two sections was described in Section 1: Introduction and Section 2: Literature Review. The Section 3: Method discusses the DSR methodology adopted in this research. The other 4 (four) sections: Artefact Description, Evaluation, Discussion and Conclusion will be discussed in the following sections.

4. Artefact description

Fundamentally, as earlier described in the previous sections, there are 3 (three) main stages in the developed framework facilitating the knowledge transfer process. These three stages are embodied in Figure 1: (1) representing the DM knowledge template using 6 ABMs; (2) generating the unique DISPLAN of ABMs representing a particular municipality and preparing the repository, and; (3) facilitating the knowledge transfer process between the unique DISPLAN to the repository. Each of these three stages is then elaborated their processes in detail that is aimed to demonstrate the building process in the three-cycle view of the Hevner's DSR framework [20]. In other words, essentially, this section shows *design as a process* of the design-cycle of Hevner's sixth principle. The detail of each stage is elaborated as follows:

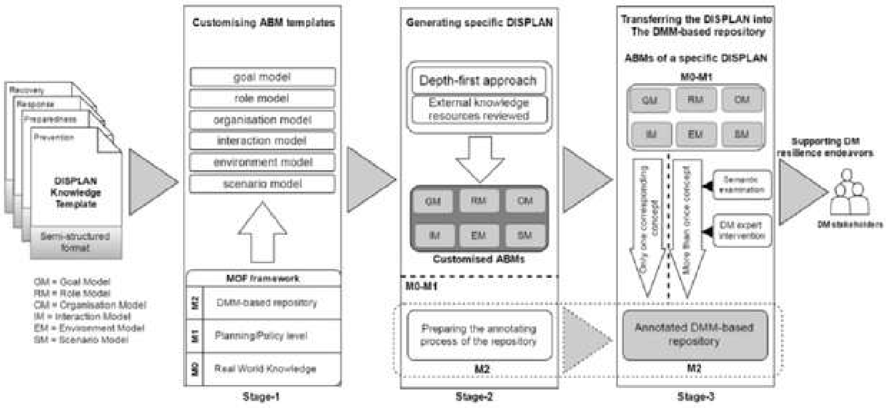

Fig. 1. The developed knowledge analysis framework to be evaluated.

4.1 Stage 1: customizing ABMs

The input of the framework is the DISPLAN template is customized by the six ABM templates:

1. A *goal model* is introduced to capture the reactiveness and proactiveness knowledge of the agents involved in the DM. In this model, roles that need to be played to achieve the goal(s) are identified. The sub-goals as subsets of the goals are also identified. This is as exemplified in Figure 3(a).
2. A *role model* is used to represent all responsibilities knowledge that needs to be played by an agent and all the constraints of those responsibilities of a role as exemplified in Figure 3(b).
3. An *organizational model* is used to represent the relationships between roles and highlight how to take in to account their relationships in a DM process. The model defines the communication channels between agents which may belong to different organizations or levels of command in a

widely dispersed disaster.

4. An *interaction model* is used to elaborate the specification of the communications between agents that play particular roles to pursue a goal. In other words, this model defines in which goal agents need to interact.
5. An *environment model* specifies the environmental constraints on activities and resources of agents. This model elaborates the resources, the activities and the roles that require them.
6. A *scenario model* binds all knowledge elements as activities that need to be undertaken in pursuing a particular goal with specific triggers and agent types. The activities are preceded by a pre-condition and followed a post-condition, as a desired state of the goal that pursued in the activities. Conditions of those activities are specified as either parallel, interleaved or sequential.

These six ABMs are envisaged to have been sufficient in representing the identified characteristics of the complex DM knowledge [21]. This DISPLAN template is obtained from the DM agencies as the authoritative to combat the disaster. This stage results the six customized ABMs. The customized ABMs are then tailored with the MOF framework to structure the knowledge elements in each model into the planning/policy (*M1*) and real world (*M0*) levels. The customising processes of *goal* and *role models* are in Figure 2. (*Note that only goal model and role model templates are shown here due to the space limit*)

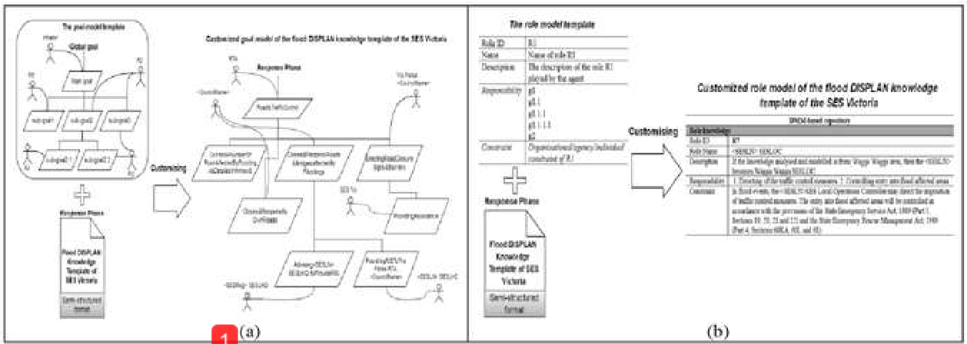

Fig. 2. Examples of customizing process of the (a) *goal model* and (b) *role model*.

The use of templates as the input instead of a unique plan increases the effectiveness and efficiency of the analysis by first tuning the ABM templates to suit the core structure of all DISPLANs. The use of templating is also common as it is seen as a key approach to effective interoperability. It helps stakeholders to quickly identify the urgent and relevant knowledge to respond to a particular activity by developing a familiar construct of actions which can easily be navigated. The early version of the framework has been partly exhibited in here [22] and evaluated in here [23]. This essay differs than its earlier versions as the improved framework in this version is resulted from the prior evaluations with different case studies. The framework is then evaluated using a new case study. Moreover, this essay differs than the previous versions as this emphasis in detail on how DSR guides and frames the research.

4.2 Stage 2: Generating six ABM DISPLANs

Once the customised ABMs are produced as discussed in Stage 1 then the ABMs corresponding to any unique DISPLAN for any area under the same jurisdiction can be generated quicker. There are 3 (three) activities take place in this stage: (1) a depth-first approach guides the knowledge engineer in generating these models more efficiently. This also potentially enables multiple knowledge engineers to develop a particular DISPLAN (but this possibility is not pursued in this paper); (2) the more detail the knowledge elements are, in particular representing the local characteristics, the better. Towards this, a pathway for knowledge transfer reflecting the local characteristics is

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added. Some details beyond of what is available in the DISPLANs are needed. Thus, a further analysis to incorporate more detail knowledge elements is by synchronising and substituting them as necessary accordingly; (3) the DMM-based repository is prepared by annotating all the 92 concepts (21, 25, 25, and 21 concepts in Prevention, Preparedness, Response and Recovery phases respectively) [11] with the AB metamodel concept, FAML [24] to guarantee the interoperability of the transfer process of the repository and the ABMs being framed by OMG-MOF framework. The DMM need to be transformed into the Agent-Based DMM as the models are in the Agent-Based paradigm. This process results the annotated DMM based repository.

4.3 Stage 3: Knowledge transfer

This is a knowledge transfer stage between the ABMs of a particular DISPLAN (*M0-M1*) in the Stage 2 to the annotated repository (*M2*). The process is conducted by mapping each of the ABMs with the corresponding concept in the DMM-based repository. In a case that there is only one corresponding concept in the repository to be mapped to, this process can be proceed directly and automatically. For instance, there is only one <<*goal*>> concept in each DM phase. Therefore, the *goal model* can be mapped to the annotated one directly. However, if there is more than one possible concept in the repository, then a DM expert is involved to map the most possible one to be mapped with based on their semantic meaning. For instance, the *scenario model* is annotated by AB FAML metamodel <<*activity*>> and in the repository there are many concepts represented by the <<*activity*>>. As such, for a knowledge element "*road and traffic control*", as there are 7 (seven) DMM concepts in Response phase represented by <<*activity*>>, namely: *MassCasaultyManagement, Rescue, Deployment, Command, Coordination, SituationAnalysis* and *InformationManagement*, the involvement of the DM expert is required to choose the most corresponding one among them for the knowledge element in the *scenario model* based on their semantic meaning.

An instantiation of the developed artefact is drawn in Figure 3. It employs a web-based technology: AJAX, PHP, Apache, MySQL and XML. In Figure 3(1), the Agent-Based modelling is processed using the first tool developed for this purpose. This process results the XML in (2). The XML is then converted to the DMM-based repository (3) developed using the second interface (4). In Figure 3(5) presents the Entity Relational Diagram (ERD) of the ABMs. Once the knowledge is deposited in the repository, the next is to map them accordingly in (6). The knowledge structure in the repository represent the 3D format in (7) and in (8) the interface to access it is created. Finally, in (9) the DM stakeholders can access by browsing and clicking each of the cubes for decision making mechanism.

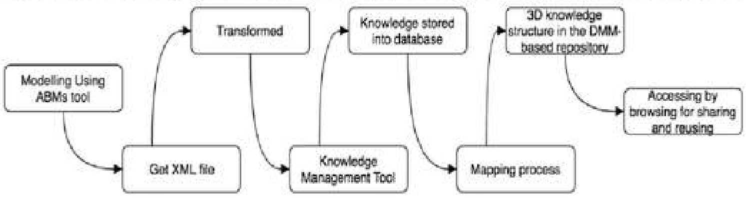

Fig. 3. The instantiation of the DM knowledge analysis framework.

5. Evaluation

As in the DSR, once built, the artefact should be evaluated at the first place. The input of the framework is the flood DISPLAN template of the SES State of Victoria, Australia, for only Preparedness and Response phases as both have represented pre- and post-disaster. The unique DISPLAN to be generated is the Moira Shire Municipality. This Municipality is chosen randomly among 80 Municipalities that are governed in 17 regions [25] to demonstrate that any city under the same hierarchy level can develop its own DISPLAN based on the template one. Both originals of the SES Victoria DISPLAN template and the Moira Shore plan can be obtained freely in the SES State of Victoria website: https://www.ses.vic.gov.au. A DM expert from the SES Victoria is engaged in this evaluation. The stages of the framework are discussed as follows:

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5.1 *Stage 1: Customizing the Six ABMs of the SES Victoria DISPLAN template*

Following the Stage 1 in Section 4, the activities in this stage produces the six customised ABMs: customised *goal model, role model, organisation model, interaction model, environment model* and *scenario model* of flood DISPLAN of the SES Victoria. These customised six ABMs will be the basis to generate the unique DISPLAN.

5.2 *Stage 2: Generating six ABMs of the Moira Shire Municipality DISPLAN*

In this stage, the six ABMs being produced from the previous stage are used to generate the six ABMs of flood DISPLAN of the SES Moira Shire Municipality. In addition, the external knowledge sources from the Appendices of the DISPLAN are used to represent the local characteristic of the Moira Shire Municipality. For instance, for the detail list of the river gauge locations is identified from Appendix C: "Flood Emergency Plan". In this stage, the repository is also prepared and readies for the knowledge transfer.

5.3 *Stage 3: Knowledge transfer*

Once the ABMs of the Moira Shire Municipality and the repository are in place, in this stage, the knowledge transfer between takes place. The DM stakeholders are able to access the knowledge in the repository by "clicking" it for the decision making process. This is as shown in Figure 3.

6. Discussion

This paper successfully presents the knowledge analysis framework in addressing the challenges of converting of the semi-structured DM knowledge to the format that can be comprehended easily. The SES Victoria DISPLAN template is used to customize the six ABMs and subsequently successfully produce the six ABMs of the Moira Shire Municipality DISPLAN prior depositing them into the repository. The DSR framework is employed to frame the research activities rigorously. A DM expert from the SES Victoria is involved since the development to the evaluation phases. In the development phase, the expert involvement is to provide feedbacks to construct the framework to work as intended. In the evaluation phase, a DM expert examine the effectivity and the efficacy of the framework. In particular, the new DM knowledge representation in the repository is unchanged and is better structured to support the decision making mechanism in the DM activities.

A case study from the SES Victoria DISPLAN template of Australia is chosen in this research with these following reasons, that: (1) it aims to ascertain the generalisability of the framework to be implemented in other areas with the same structure. This is due to the initial evaluation of the framework in the previous evaluation with the case study from the SES NSW State, Australia [26, 27]. In other words, this framework paves the way to be potentially implemented in other countries with the same government structure; (2) The flood disaster is taken in this evaluation due to the fact that it is not only the issues in under-developed countries but also the developed ones. In fact, although it is largely a dry continent, the Australia now experiences severe flooding across its States [28].

7. Conclusion

Unlike other approaches to conceptualise the complex domain, e.g. ontology, the ABM paradigm used in this research lends themselves to represent the complex characteristics of the DM domain. The ABM templates represent the know-how organisational knowledge is acknowledge and structured in the representative templates for further developments. In particular, this research differs than Othman *et al.* work's [11] in how to recognize and drill down complex characteristics in DM domain. The research aims to build a knowledge analysis framework in DM domain. It then evaluates using a case study from the SES State of Victoria Australia. The processes are orchestrated by utilising the DSR methodology in IS. This is essentially the contribution of the research to the DM domain knowledge. As for the practical contribution, the validated framework potentially helps the DM stakeholders to better structure their DISPLANs for a better decision making process is the DM activities. In particular, it helps the DM stakeholders to the DM knowledge more accessible, searchable and assisting the comprehensive arrangements.

For other countries that have the similar hierarchy government structure such as Indonesia (central – province – regency governments), this framework potentially can be adopted and implemented by the DM agencies (BNPB/BPBD – National/Local Disaster Management Agencies) to develop their DISPLANs efficiently. Developing ABM templates of a particular DISPLAN at the first place in central government and allowing them to be adopted and synchronised by provincial/regencies governments based on their local wisdoms to create their own plans without constructing them from scratch. This process is effectively guided by a depth-first approach being introduced in this research. The use of ABM paradigm to be used DM domain paves the way for it to be adopted and adapted to capture the complexities in other complex domains. In addition, the use of DSR is with the aim to demonstrate as to how it is utilised systematically in IS research.

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