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Complex systems simulation for risk assessment in flood incident management

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Abstract: This paper proposes a complex systems methodology for risk assessment in emergency management and response systems. The methodology is applied to a concrete case, the flood incident management system (FIM) operated by the British Environment Agency.

Flood incidents are one category of natural catastrophes, disasters or emergencies. The occurrence of emergencies is determined by the operation of complex systems. The management of and response to emergencies are also determined by the operation of complex systems. Flood incident management (FIM) systems are one kind of emergency management system, so a complex systems based approach is necessary for effective flood incident management because:

- flood incidents emerge from properties and behaviour of complex systems;
- flood incidents and procedures for response to flood incidents are complex systems;
- emergent behaviour of these systems may not be obvious from more simplified modelling – complex systems modelling allows emergent behaviour of the system to be identified;
- it is essential to assess not only the probabilities and consequences of the failure of individual components, but the impact on the whole, complex system of individual component behaviour;
- such an approach will help to decide how to mitigate or manage the risk and uncertainties inherent in the whole system of FIM.

For FIM a practical approach to risk management from a complex systems point of view is required to model real systems. To realise such a practical approach the following recommendations are made.

- Use multi-agent simulation to model, in an intuitive way, the systems involved. Multi-agent simulation is particularly suitable to simulate complex systems, as it offers a natural way to describe system components and their interactions and can be used effectively to simulate such systems to study their behaviour. An emergency response system can also be described in a very natural way as a system of interacting agents; therefore, multi-agent simulation can be used to gain insight into such a system.
- Combine multi-agent simulation with Bayesian decision networks to model probabilistic decision making by agents. Bayesian decision networks are suitable for describing probability and risk aspects of an emergency response system, because they offer an intuitive way to define probabilities of different outcomes on the level of individual system components. These probabilities need not be objectively defined, but can be based on the judgement of experts and FIM staff with practical knowledge of the system. They offer a method to integrate component-level knowledge in an outcome at the whole-system level. A proposal is made for a possible implementation of such an approach for the FIM system of the Environment Agency.
- Use evolutionary computation to improve FIM by optimising agent behaviour in relation to whole system behaviour.
- Consolidate the above approaches in an extended Emergent Models methodology suited to emergency management and response in general and to FIM in particular.

Keywords: *Emergent Models, Complex Systems, Risk Assessment, Flood Incident Management*

1. INTRODUCTION

Flood incidents are one category of natural catastrophes, disasters or emergencies. The occurrence of emergencies is determined by the operation of complex systems. Complex systems consist of entities that interact with each other to produce the behaviour of the system as a whole (Bar-Yam 1997, p. 1). An important characteristic of a complex system is that the properties and behaviour of the whole are emergent; that is they cannot simply be inferred from the properties and behaviour of the components (Bar-Yam 1997, p. 10; Holland 1998). Many relatively simple entities interact in relatively simple ways to give rise to emergent phenomena that could not have been predicted easily from the definition of the entities and their interactions. In the case of natural disasters this is already apparent at the highest level of system description, where a system that produces disasters is described as only two interacting subsystems:

- the natural environment, including extreme natural events such as floods or earthquakes;
- human society, including society's risk taking and vulnerability.

There are different views of the interaction of these subsystems to produce casualties and damage, summarised by Alexander (2000, p. 227-228) as follows:

extreme natural events *act upon* risk taking and vulnerability *to produce* casualties and damage	risk taking and vulnerability *interact with* extreme natural events *to produce* casualties and damage	risk taking and vulnerability *produce* casualties and damage *when there are* extreme natural events

It is already apparent that emergencies are produced in complex systems in which it is far from obvious how to define unequivocal cause and effect relations.

Both the management of and response to emergencies are determined by the operation of complex systems. Flood incident response systems are one kind of emergency management system. An incident may be defined as an occurrence that is caused by either humans or natural phenomena and requires action to prevent or minimise loss of life or damage to property.

Emergency management has been based in the past on a rigid hierarchical structure of authority, but more emphasis is now given to adaptability. For example, the incident command system used in the USA is an all-hazard incident management system emphasising coordination through consultation and flexibility, the constitution of task forces to deal with problems as they arise, and consensus as to the goals to be achieved by a process of delegation, participation and mutual involvement (Alexander 2000, p. 164-165). In addition to order and central planning, improvisation is vital for emergency management, and there will be emergent groups, emergent norms and emergent social structure (Alexander 2000, p. 166). The incident command system is an example of the current trend in thinking about emergency response, which acknowledges that emergency response systems are complex systems.

This trend is also exemplified in current British government regulations on emergency preparedness and response, as described in *Emergency Preparedness: Guidance on Part 1 of the Civil Contingencies Act 2004*, and its associated regulations and non-statutory arrangements, and *Emergency Response and Recovery: non-statutory guidance to complement Emergency Preparedness*. These government regulations are the context in which the work of the Environment Agency is carried out. The Environment Agency operates a flood incident management system (FIM) to respond to emergencies caused by flooding. Risk assessment is an important aspect of FIM and the Environment Agency is aware of the consequences of risk at the level of system components on the behaviour of the whole FIM system. The present research addresses this concern.

I conclude that a complex systems-based approach is necessary for effective emergency response in general and FIM in particular because: emergencies such as flood incidents emerge from properties and behaviour of complex systems; emergency response systems such as FIM are complex systems too; emergent behaviour of these systems may not be obvious from more simplified modelling – complex systems modelling allows emergent behaviour of the system to be identified; it is essential to assess not only the probabilities and consequences of the failure of individual components, but the impact on the whole, complex system arising from individual component behaviour; such an approach will help to decide how to mitigate or manage the risk and uncertainties inherent in whole emergency response systems such as FIM.

Many approaches to modelling and analysis of complex systems have been proposed. In a review of complex systems methodologies I have identified the ones most appropriate for the application area of FIM. These methodologies are presented in section 2. An application to emergency response systems is proposed in Section 3 with the example of the Environment Agency's FIM system.

2. COMPLEX SYSTEMS METHODOLOGIES

The study of complex systems requires methods of analysis and simulation with characteristics such as (Bar-Yam 1997, p. 8-9): looking at parts of a system in the context of the whole system and its environment, using adapted experimental tools, theoretical analysis or computer simulation; not assuming that a system is smooth and uniform or that local details do not matter for larger scale system behaviour; taking into account that the behaviour of complex systems depends on many independent pieces of information and not on just a few parameters. In this section I assess the suitability of some complex systems methodologies for application to risk assessment in FIM.

2.1. Evolutionary computation

Evolutionary algorithms are general problem-solving algorithms inspired by the evolution of organisms, interpreted as an optimisation process. They utilise the reproduction, random variation, competition and selection of contending individuals in a population to find an optimal solution to a problem (Bäck et al. 2000). In general, evolutionary algorithms do not find globally optimal solutions, but only approximate solutions. Various kinds of evolutionary algorithms have been developed, such as evolution strategies (Bäck et al. 2000, p. 81-88), evolutionary programming (Bäck et al. 2000, p. 89-102), genetic algorithms (Bäck et al. 2002, p. 64-80; Holland 1975) and genetic programming (Bäck et al. 2000, p. 103-113; Koza 1992). Evolutionary algorithms are often a good tool to solve system identification problems. System identification aims to identify the essential characteristics of a system. If data are subject to random noise, an exactly optimal fit to the data may even be undesirable and an approximate fit an advantage.

To design an optimal, or at least good, FIM system is a system identification problem, so evolutionary algorithms could be applied. We would have to define what is to be optimised, for example to minimise loss of life, minimise damage, maximise appropriateness of flood warnings or some combination of these and/or other success criteria. Further, it would be necessary to define a set of possible changes that could be made in the FIM system, for example to improve reliability of forecasts, decrease risk of communication failure, etc. If it is possible to evaluate for each change what the impact is on the success criteria, evolutionary algorithms can be applied to select the most appropriate changes to be made in the FIM system.

2.2. Bayesian networks

Bayesian networks describe systems in which elements in a situation are causally connected, with conditional probabilities associated with the connections (Charniak 1991). They are used to determine probabilities of states of events in the described situation, when some part of the situation has been observed. Bayesian decision networks, often described by influence diagrams, are an extension of Bayesian networks suitable for decision support (Shachter 2005). An example is given in Figure 3. Most nodes are the same as those in a Bayesian network, with added decision nodes and a value node. The network is used to calculate the probable impact of a decision (for example, make a tactical warning) on the value, that is the final result of the network on something desirable, such as life or economic value.

Bayesian decision networks appear to offer a particularly relevant formalism to describe probability and risk aspects of a FIM system because: they offer an intuitive way to define probabilities of different outcomes at the level of individual system components; these probabilities need not to be defined objectively, but can be based on the judgement of experts and Environment Agency staff with practical knowledge of the system; they offer a method to integrate component-level knowledge in the outcome at a whole-system level.

2.3. Multi-agent simulation

In multi-agent simulation active entities in the world and their behaviour are represented in a computer as software entities called agents. These make it possible to represent a phenomenon as the result of the interactions of a set of autonomous agents (for example, Holland 1998, p. 116-118; Ferber 1999, p. 36; Wooldridge 2002). It can be applied to any system composed of individual entities. An agent is an entity with tendencies or objectives it tries to satisfy by acting in an environment and communicating with other agents, using its resources and skills. Its actions depend on its perception and representation of the environment, and on communications it receives (Ferber 1999, p. 9). In other words, an agent is proactive, with a goal-directed behaviour, and takes the initiative to satisfy its objectives. It is also reactive, as it perceives and responds to its environment. Finally, it has social ability and interacts with other agents (Wooldridge 2002, p. 23).

Multi-agent simulation is particularly suitable to simulate complex systems, as it offers a natural way to describe system components and their interactions and can be used effectively to simulate such systems to study their behaviour. A FIM system can also be described in a very natural way as a system of interacting agents. Therefore, multi-agent simulation could be used to gain insight into such a system.

2.4. Emergent Models

We have seen how complex systems can be modelled using multi-agent simulation. We have also seen how evolutionary algorithms, and in particular genetic programming, are general-purpose algorithms to solve a variety of optimisation problems. In Stolk (2005) ideas from multi-agent simulation and from evolutionary algorithms are combined in a novel methodology to discover emergent macro-level regularities or patterns in simulations of complex systems. These macro-level regularities are models of the behaviour of macro-level agents, in other words emergent models. Therefore, the new methodology is called the Emergent Models methodology. It defines ways to derive macro-level behaviour from micro-level properties and behaviour, and discovers models at the macro-level implied by those that describe the micro-level. This methodology can also be applied to the inverse problem of discovering micro-level behaviour of the composing entities of a complex system from data on its macro-level properties and behaviour. The Emergent Models methodology is a powerful methodology to study complex systems in general and FIM systems in particular.

Organisations are good examples of complex systems suitable for simulation using multi-agent approaches as described, for example, by Ferber (1999) and Wooldridge (2002). First, in an organisation relatively autonomous entities (organisational units, individuals) with their own behaviour respond to environmental stimuli, as well as satisfying goals. Second, organisational units and individuals in an organisation interact with each other and with processes in their environment. Agents can simulate this by appropriate communication capabilities. Third, organisations are structured hierarchically. Micro-level entities act together to constitute macro-level entities. Macro-level properties and behaviour are derived from micro-level properties and behaviour.

Thus, emergent models of group behaviour describe important phenomena in organisations, as they directly address the fundamental problem of emergence: how to derive properties and behaviour at the group level, or macro-level, from those at the individual level, or micro-level? Emergent Models is a systematic method to derive macro-level properties and behaviour and to obtain models on the level of group agents in computer simulations, as illustrated by Figure 1. Alternatively, the methodology can be applied to derive individual or subsystem characteristics, given desired whole system behaviour, in a way analogous to the derivation of genetic networks from whole organism behaviour described by Stolk (2005).

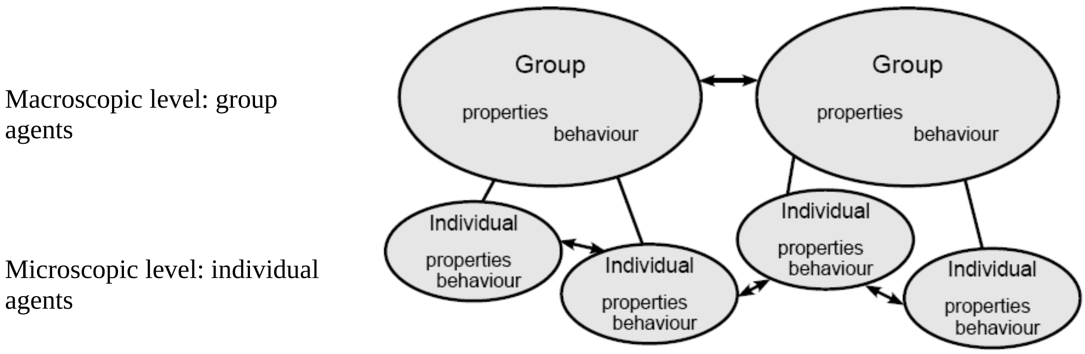

Figure 1. Levels in a multi-agent simulation.

2.5. A practical complex systems approach to flood incident management

To be realistically applicable to a FIM system, a complex systems approach should be practical enough to enable modelling of real systems – much complex systems research is devoted primarily to demonstrating general and abstract principles of complex systems. It should take account of the particular characteristics of a FIM system, such as lack of complete information about the state of a system and a precise definition of all its elements, as well as probabilistic aspects of the system. The approach should be suited to incremental improvements to the existing system, as long as a fundamental restructuring of the existing system is not considered a realistic option in the short term.

A practical approach based on these considerations to assess the 'weak links' in the FIM process can be developed as described in Section3.

3. RISK ASSESSMENT IN FIM BASED ON COMPLEX SYSTEMS

The Environment Agency's FIM system is a complex system. Complex systems can be modelled by multi-agent simulation. Therefore, the proposed methodology includes modelling FIM using multi-agent simulation. Risk is an important aspect of FIM. In the context of artificial intelligence much research has been done on Bayesian networks as a method to analyse uncertainty and risk. Bayesian networks contain nodes that represent causes and effects with associated conditional probabilities. Bayesian decision networks are an extension of Bayesian networks particularly suited to decision making in circumstances of uncertainty. In addition to cause and effect nodes, they contain nodes that represent decision variables and nodes that represent objective variables. Decisions are evaluated by inference algorithms, such as the ones described by Charniak (1991) and Schachter (2005). Therefore, the proposed methodology includes the use of Bayesian decision networks to model risk and uncertainty. In the proposed methodology multi-agent simulation and Bayesian decision networks are integrated in a coherent conceptual framework for risk assessment in FIM.

The Environment Agency's flood incident management (FIM) model describes processes at several levels: the FIM end-to-end process and activity diagrams at levels 1, 2 and 3. Part of the FIM model defines processes related to flood warning and response. A simplified representation of these processes is given in Figure 2. We see that FIM processes are described as interacting components at several levels of detail. The top-level end-to-end process is refined in successively more detailed sub-processes.

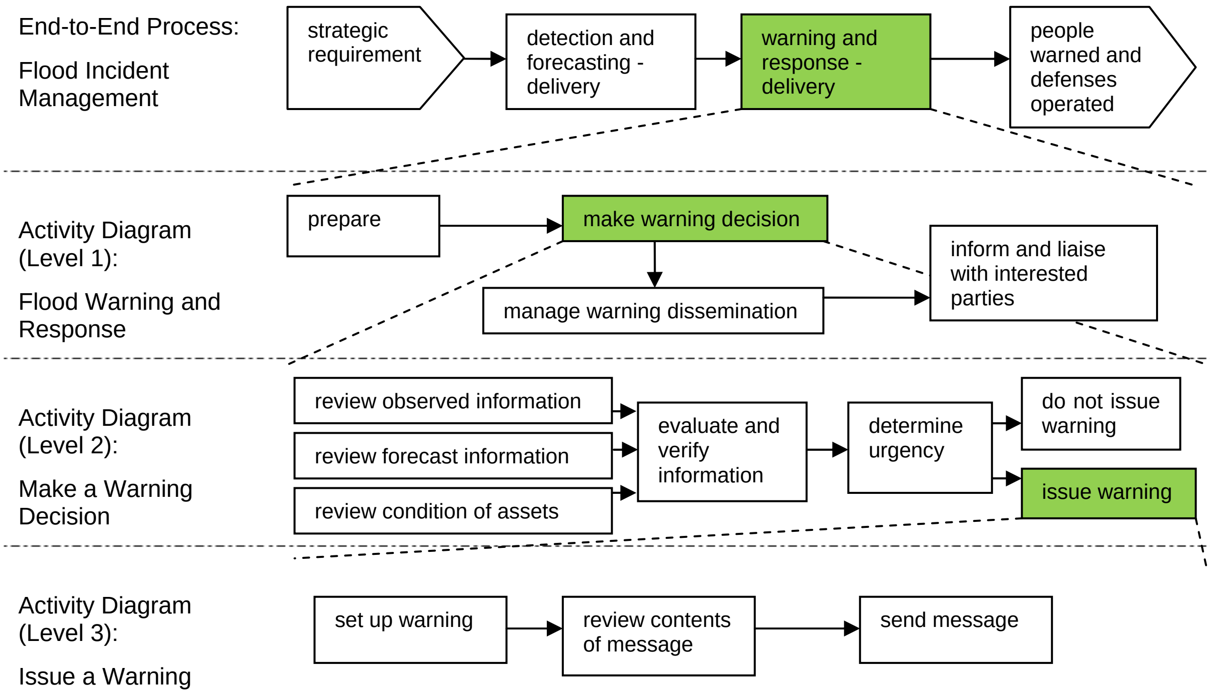

Figure 2. Flood incident management processes.

The Environment Agency's FIM Model can serve as a basis for a multi-agent model of the FIM process. Loosely, every box in a diagram of the model corresponds to an agent. The behaviour of an agent consists of: observing its environment; processing information obtained from observations; acting on its environment. Examples of agents identified in the process diagrams related to flood warning and response are shown in Table 1. Generic agent behaviour and specific agent behaviour are shown in the first and second columns.

Bayesian decision networks are used in this multi-agent system to model probabilistic decision making by each agent. Actions by agents lead to results with associated probabilities. Probabilistic nodes of the diagram represent aspects of agent behaviour, including uncertainties in observations (for example, reliability of observed or communicated information), information processing (for example, cognitive mechanisms, reasoning errors, or faulty computing equipment) and actions (for example, faulty communication equipment, or physical obstruction). Decision nodes represent decisions made by the agents. As an example, a Bayesian decision network model of a warning decision agent is shown in Figure 3. The impact of uncertainty in the decisions by each agent on the behaviour of the whole system can be analysed by running multi-agent simulations.

Table 1. Flood incident management agents.

Warning and response delivery agent			
Behaviour	*Object of behaviour*	*Uncertainties*	*Probability*
Observe	Detection and forecasting information	Have correct information Do not have correct information	p_1 $1 - p_1$
Process information		Information processed correctly Information not processed correctly	p_2 $1 - p_2$
Act	Issue warning; operate defences	Warning issued Warning not issued Defences operated Defences not operated	p_3 $1 - p_3$ p_4 $1 - p_4$
Warning decision agent			
Behaviour	*Object of behaviour*	*Uncertainties*	
Observe	Review of observed information Review of forecast information Review of condition of assets	Have correct information Do not have correct information	p_5 $1 – p_5$
Process information	Confer with officers Evaluate and verify information Identify what other information is needed Determine urgency required Consider external influences	Information processed correctly Information not processed correctly	p_6 $1 – p_6$
Act	Make decision to issue a warning Make decision not to issue a warning	Warning issued Warning not issued	p_7 $1 – p_7$

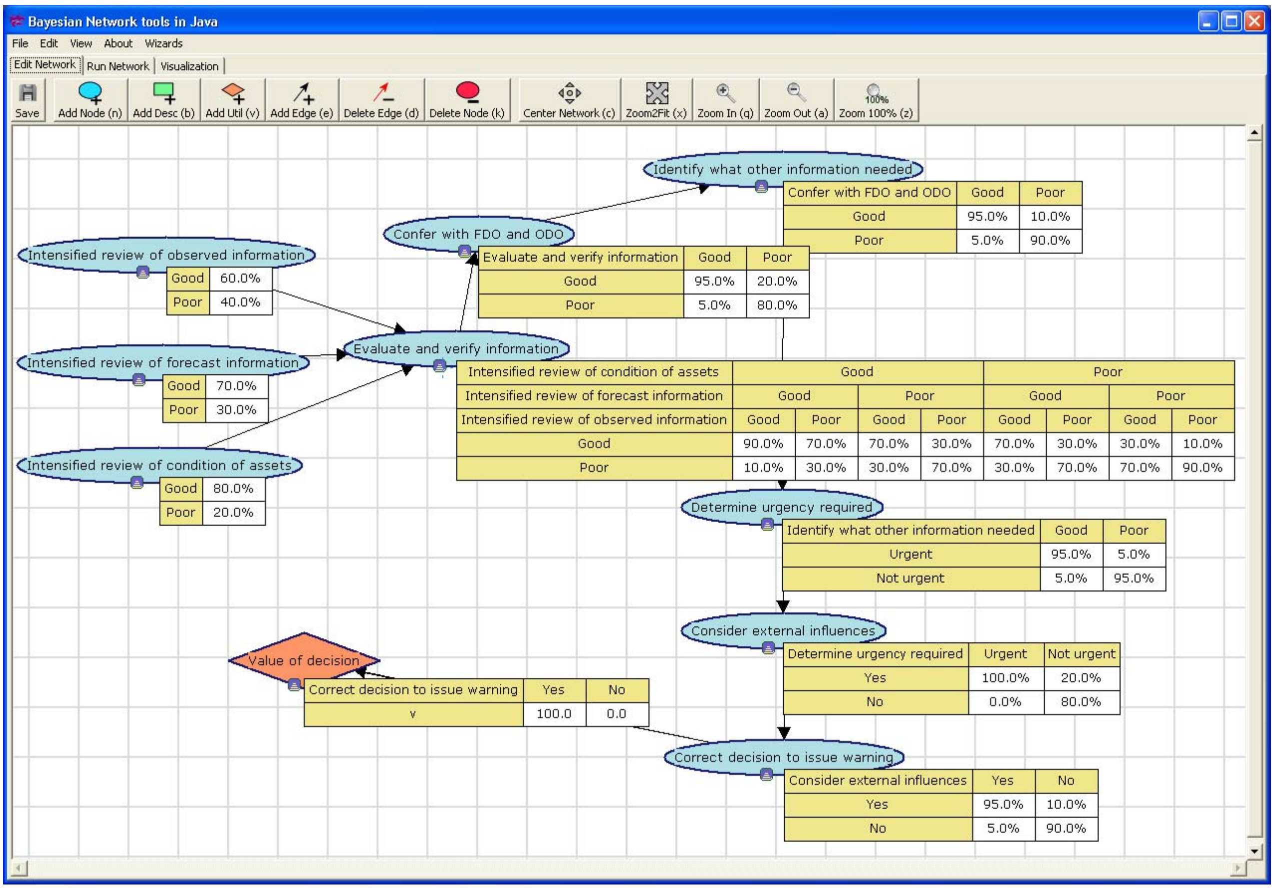

Figure 3. Warning decision agent modelled as Bayesian decision network.

Probabilities associated with uncertainties in agent behaviour are shown in the last column of Table 1. Incorporating these probabilities in a multi-agent simulation of flood incident response would make it possible to model risk and uncertainty in the context of a complex system model and to take advantage of known algorithms to analyse Bayesian decision networks. It is essential to have a way to estimate the probabilities of outputs of each system component, depending on its inputs. The number should reflect the best information available. This can be done in several ways, for example, using information on the behaviour of the components as assessed by scientific theory, information on past behaviour, probability estimates of experts and probability estimates of FIM practitioners.

Risk can no longer be defined in the traditional way as the probability of one event occurring multiplied by its consequences. It is inherent in a whole-system approach that it becomes impossible to associate risk with a single event. However, it is possible to evaluate the expected effect on the outcome of the whole system of different probabilities associated with decisions by the agents composing the system.

4. CONCLUSION

For FIM a practical approach to risk management from a complex systems point of view is required to model real systems. To realise such a practical approach I recommended that the Environment Agency and other organisations responsible for emergency response and management:

- Use multi-agent simulation to model, in an intuitive way, the systems involved. Multi-agent simulation is particularly suitable to simulate complex systems, as it offers a natural way to describe system components and their interactions and can be used effectively to simulate such systems to study their behaviour. A FIM system can also be described in a very natural way as a system of interacting agents; therefore, multi-agent simulation can be used to gain insight into such a system.
- Combine multi-agent simulation with Bayesian networks to capture risk and uncertainty. Probability estimates can be incorporated via expert judgements. Bayesian networks are a relevant formalism to describe probability and risk aspects of a FIM system, because they offer an intuitive way to define probabilities of different outcomes on the level of individual system components. These probabilities need not be objectively defined, but can be based on the judgement of experts and staff with practical knowledge of the system. Bayesian networks can be used to integrate component-level knowledge in an outcome at the whole-system level.
- Use evolutionary computation to find optimal solutions to the design of system components and their interactions, given a desired behaviour of the system as a whole.
- Consolidate the above approaches in an extended Emergent Models methodology suited to emergency response and, in particular, to FIM.

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