A Human-Centered Conceptual Model of Disasters Affecting Critical Infrastructures

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ABSTRACT

Understanding the interdependencies of critical infrastructures (power, transport, communication, etc.) is essential in emergency preparedness and response in the face of disasters. Unfortunately, many factors (e.g., unwillingness to disclose or share critical data) prohibited the complete development of such an understanding. As an alternative solution, this paper presents a conceptual model – an ontology – of disasters affecting critical infrastructures. We bring humans into the loop and distinguish between the physical and social interdependencies between infrastructures, where the social layer deals with communication and coordination among representatives (either humans or intelligent agents) from the various critical infrastructures. We validated our conceptual model with people from several different critical infrastructures responsible for disasters management. We expect that this conceptual model can later be used by them as a common language to communicate, analyze, and simulate their interdependencies without having to disclose all critical and confidential data. We also derived tools from it.

Keywords

Disaster management, ontology, critical infrastructure interdependency, conceptual modelling, emergency preparedness, metamodel, UML.

1. INTRODUCTION

Recent disasters have made us aware that critical infrastructures are highly dependent on each other since the failure of one can lead, in a cascading manner, to the failure of others. Critical infrastructures are those that humans heavily depend on in their normal daily life: power generation and transmission, telecommunication, water supply, transportation, and banking. Some understanding of the *interdependencies* of critical infrastructures is essential to prepare, response, and recover from a disaster.

Unfortunately, it is not a straightforward exercise to identify these interdependencies. First, people in different critical infrastructures use different and somewhat inconsistent terminologies, as these critical infrastructures were developed independently. Although attempts have been carried out to explain and define common terms (e.g., Peerenboom, 2001), they were done in natural language, which itself can have multiple interpretations and sometimes difficult to be precise. Second, people are unwilling to disclose critical information: most infrastructures were developed with no or little security in mind and sharing critical information will result in many serious security concerns. Third, very few people (or even none) in the disaster management area have experience dealing with actual major disasters. They can only prepare their infrastructures according to what they can foresee. Although it is possible to consult those who had the experience, the unwillingness to disclose critical data still gets in the way. In sum, the challenge is how to move forward in understanding the interdependencies of critical infrastructures with incomplete information and inability to fully validate results.

In this paper, we present a conceptual model – an ontology – of the impact of disasters on populations, focusing in particular on the effects that damages on interdependent critical infrastructures have on the populations. Rather than expressing the disaster impacts in financial terms, which could lead to decisions adverse to the population, the model uses a concept of wellness or well-being of population cells, and organizes around it other important concepts according to the way they contribute to or degrade the wellness of these geographic cells. Our aim is to use this ontology to resolve the inconsistent and different terms used in different critical infrastructures as mentioned in the previous paragraph. To avoid having to disclose all critical data, we bring humans into the loop and distinguish between the physical and social interdependencies, where the social layer deals with communication and coordination among representatives (either humans or intelligent agents) from the various critical infrastructures. We then use this model as the basis for a family of disaster simulators used to analyze weaknesses in the infrastructure or in their interdependencies, physical and social, or to support disaster rehearsal by emergency organizations, or to help decision-making during an actual disaster.

In studying the interdependencies among critical infrastructures, several ontologies have been proposed to support the various aspects of dealing with interdependencies, but they do not serve our needs well as explained in Section 2.2.

The remainder of this paper is organized as follows. Section 2 discusses background and related work. Section 3 presents our proposed ontology. Section 4 provides some evaluations of our own work, while Section 5 shows how our ontology can be used to build tool support.

2. RELATED WORK

In this section, we first situate our work in the context of disaster and hazard research, then we look at what was done regarding ontology of disaster, and finally models and methodologies for Modelling Critical Infrastructure.

2.1 Disaster and hazard research

Natural hazard research was originally conducted by social geographers who viewed natural disasters as the result of interacting natural and social forces (Mileti, 1999; Tierney *et al.*, 2001). Proponents of this approach asserted that disaster losses can be reduced through adoption of hazard adjustments such as land-use controls, hazard-resistance construction practices (e.g. building codes), public works (e.g,. dams and levees), and implementation of warning and evacuation systems.

In contrast, sociologists worked on disaster research, which focused on human behavioral response to hazards impacts (Mileti; Tierney *et al.*). Specifically, they defined disasters as external events that disrupt the social order by breaking down the economic production and failing the social system, and events requiring the interventions from outside of the disaster zone.

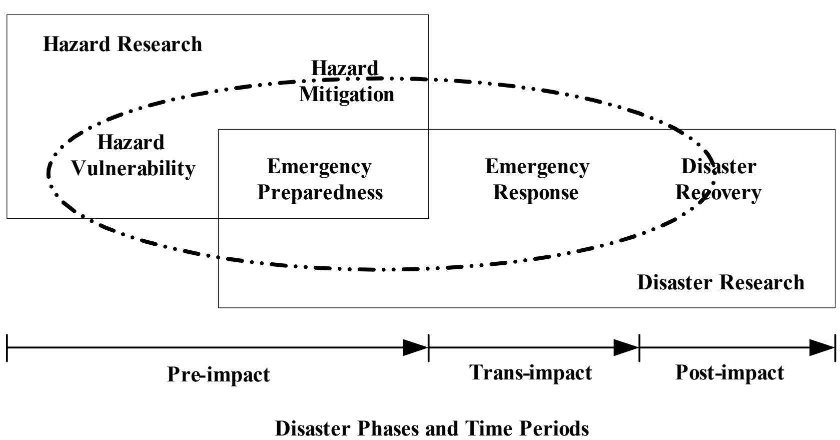

Figure 1: Substantive Foci of Hazards and Disaster Research (Tierney et al., 2001)

Figure 1 illustrates the linkages between hazard and disaster research. Our work straddles hazards research and disaster research, and our model should support the study of disaster pre-impact, during the impact and post-impact, but may not extend to long-term upstream: the broader social context such as social vulnerabilities, and downstream: long-term recovery.

2.2 Disaster ontologies

Existing languages or models used to describe disasters do not fit our needs for various reasons.

The Common Alerting Protocol (CAP) is an XML-type language for describing disaster events (OASIS Committee Specification, 2005). It is useful during a disaster but lacks the constructs to describe post-impact events.

Hoogendorn *et al.* (2005) provide constructs such as role, input, and output to model the organizations involved in the disaster planning. They also have a way to keep track of the events in the disaster plan and a language to show organisational change. However the model does not take into account the physical infrastructure affected in a disaster.

El-Diraby (2005) proposes a more concrete model where there are five main entities affected by a disaster: actors, projects, resources, processes and products. Two supporting concepts are mechanisms which can be described as technology, techniques or theories used to support the actor in its production. Constraints are things in the environment that can hamper the process. The model is used to show how we can describe what an actor does in an environment. El-Diraby goes on to show that the product can also be split into a metamodel and creates different lexicons for different products (pipes, cables, structure, pumps, devices, etc.). However, the interdependencies between infrastructures can only be indicated by saying they are involved in the same process rather than how they are truly connected. Also the ontology seems to be very general and could be applied to any process. There is no clear delineation of concerns such as the difference between the population and agents who carry out repairs to the infrastructure.

The model we are proposing in this paper is different for several reasons. First, it is more than semantic interoperability because we are providing a common ontology that can be used by researchers and practitioners who are dealing with infrastructures and disasters. We also do more than the formal modelling of disaster plans because we incorporate the physical infrastructure as well as the interrelationships between actors in the disaster plan. Lastly, our model can have actors interacting with one another without being tied to projects or processes. We also have a generalised framework for the infrastructure which can replace the specific terminology of the parties involved (e.g., a transport component rather than a pipe or cable).

2.3 Other Models and Methodologies for Modelling Critical Infrastructure

Conrad *et al.* (2005) have created their own version of an infrastructure interdependency model. However, it does not distinguish humans from infrastructure elements. Similarly, a survey of existing methodologies to model critical infrastructure shows that many do not include the "human in the loop" that our model has (Pederson *et al.*, 2006). The methodologies that do include the human aspect use variables to simulate them, while we have a detailed representation of humans using intelligent agent concepts. In addition to physical layer simulation, our framework thus also aims to aid practitioners in coordinating their manual procedures.

3. THE MODEL

According to Uschold *et al.* (2004), there are different approaches to ontologies (see Figure 2). At one extreme, there are lightweight ontologies that may consist of terms only, and at the other end, there are formal ontologies and

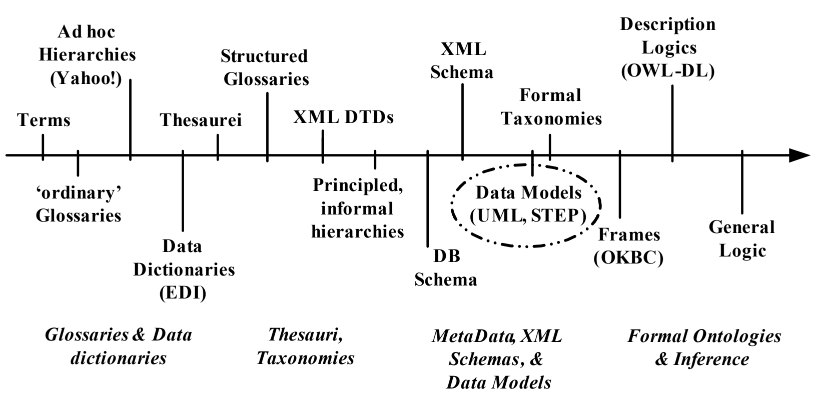

Figure 2 Kinds of Ontologies (adapted from Uschold et al., 2004)

inferences. We use ontologies for common access to information and as the basis for software development. The oval in Figure 2 specifies our work comparing to other ontologies on the spectrum. We also use the Unified Modeling Language (UML) 2 for describing our models (Fowler, 2004). Figure 3 gives a short key to the main symbols of UML.

We first provide an overview of our conceptual model, and then elaborate each 'package' in the model in a separate section. Our model is organized around four groups of concepts (See Figure 4):

1. Concepts to describe a *region* and the *people* that occupy it, and their well-being
2. Concepts to describe the various *infrastructures* that serve this region
3. Concepts to describe *events* such as a disaster and its impact on people, directly or indirectly through the infrastructures.
4. Concepts to describe *communication* and *coordination* between infrastructures, and with the regions and people.

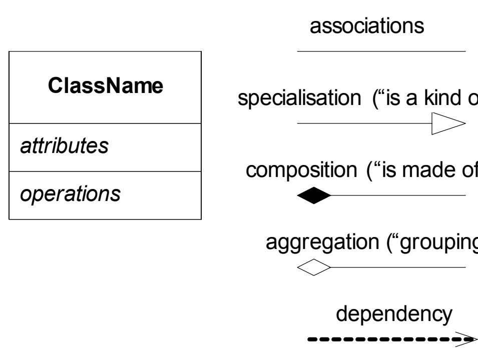

Figure 3: UML key symbols

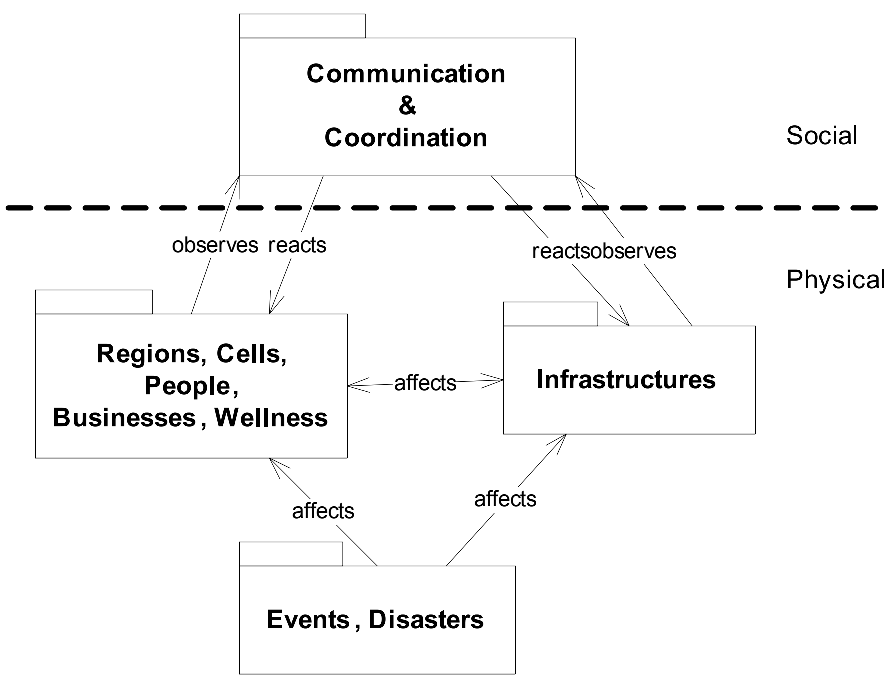

Figure 4: The four packages of the model.

3.1 Wellness and Cells

3.1.1 Individual Wellness

If we were to ask people how they feel following a disaster, we could rank their state on a simple scale, ranging from: “Everything is absolutely fine” to “Immediate death”, with a few states in-between.

Many factors are affecting our *individual wellness*; some rather immediate, such as the air we breathe, shortly followed by our access to food and water, then shelter and power, especially in very cold areas, then communication and transportation, and finally our ability to sustain some economic activity. Wellness could be thought of two components: physical wellness, and psychological wellness, but for the sake of simplicity we’ll defer this improvement.

3.1.2 Cells and Collective Wellness

As it is not quite feasible to consider each individual human being in a region, and reason about his or her wellness, which may depend on many individual factors: age, health, wealth, etc., we are going to look at aggregates: clusters of human beings that are located in the same area and are very likely to share the same level of wellness (with some individual differences).

We define a *Cell* as an entity that has a geographic location (an area), that contains a certain number of people, and has also an attribute of Wellness, called the Collective Wellness.

For example, a cell maybe a city block, a high-rise building, or some specialized area that play an important role in a disaster, such as an hospital, or a police station.

In our model we distinguish several kinds of cells (see Figure 5):

- *Residential cells*, containing people.
- *Government cells*, containing people that play a special role in the case of disasters, such as police, fire halls, government, army, etc.
- *Economic cells*: areas where commercial or industrial activities are conducted, as their wellness maybe affected differently, and their impact on the overall population wellness may be deferred in time. Some economic cells are more ‘critical’ than others in case of disaster: hospitals, food storage or production, and as we will see later, infrastructure control cells, which are closely related to the agents who control the infrastructures.

We will also see later that another criterion to define a cell is that it has a connection point to each of the infrastructures that serve it.

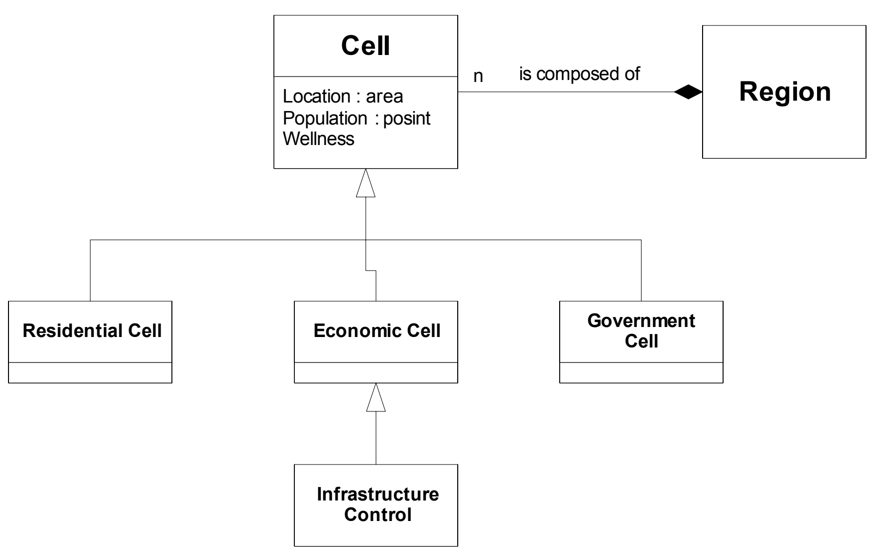

Figure 5: Regions, Cells, and Wellness

A collection of cells forms a *Region*; to simplify the model, we assume that cells do not overlap and that they form a kind of "tiling" of the region.

3.2 Resources and Infrastructures

Some of the factors that affect the wellness of a cell are dependent on various infrastructures: the electrical grid, the network of streets and road, the water supply.

A *Resource* is something that contributes significantly to wellness. An *Infrastructure* is that thing that produces and transports a given resource to the cells. For example the Electrical Power Grid produces and transports electricity to all cells; the water distribution system brings water to the cells. Some resources are "negative resources": things that must be taken away from the cells to improve wellness: sewage and garbage, but they can be represented by the same concepts.

Although there exist very detailed and complex representations for each type of infrastructure, we can simply model them for our purpose as graphs, or transport networks. An infrastructure is made of *infrastructure elements*. There are *static, passive elements* that just carry a resource from a node of the graph to another one: a road segment, a power line, and *active elements* that produce, or transform or convert a resource, and that are likely to be connected to other infrastructures: a water pumping station, a telephone switch, an electrical substation, for example.

Infrastructure elements have a *state*. Similar to the individual wellness, we can define a simple scalar scale for the state of an infrastructure element, representing its current ability to handle or transport the associated resource, its health.

The *operational status* of an infrastructure element depends on its state, and also on the state and status of adjacent infrastructure elements. A water main maybe functional, but may carry no water because the water pump it is connected to is down, or because the water pump receives no water to pump.

Infrastructure elements also have a *geographical location*, and therefore can be mapped onto a region, and in some cases physically overlap other infrastructure elements, from the same or from another resource: a bridge may carry a water main, and an optical fiber.

Infrastructure elements are connected to other infrastructure elements, forming graphs that we call "an Infrastructure" (see Figure 6).

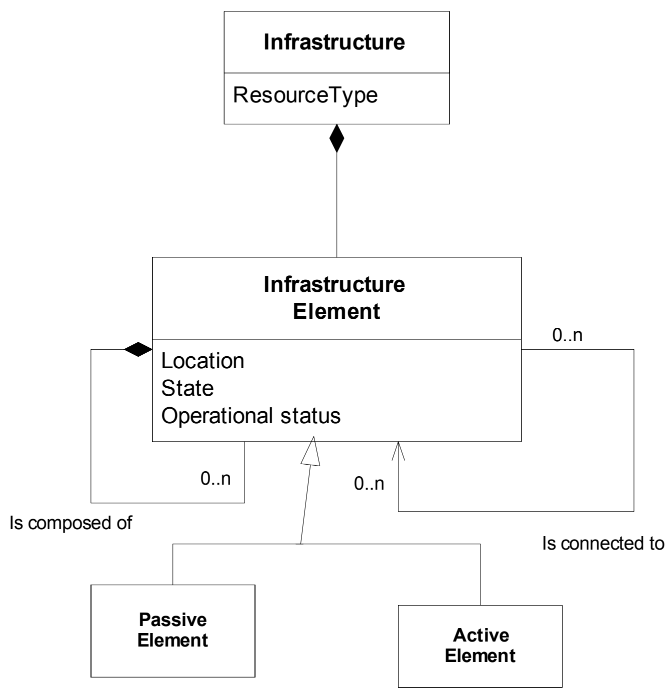

Figure 6: Infrastructures

3.3 Connecting cells and infrastructures

We are interested in the detailed state of every elements of an infrastructure, only inasmuch as they affect the wellness of cells; that is, we only care in our model about the operational status of a specific subclass of infrastructure elements, called *Distribution points*, where the resource managed by the infrastructure is made available to the cell.

Associated with the various types of cells are internal functions that modify the wellness of the cells, based on the status of the distribution points. So a cell is associated to one or more distribution point for the various infrastructures. This establishes also a *Resource dependency*: a cell is dependent on a subset of an infrastructure for maintaining its wellness. Distribution points represent mutual properties between cells and infrastructures. All these are shown in Figure 7.

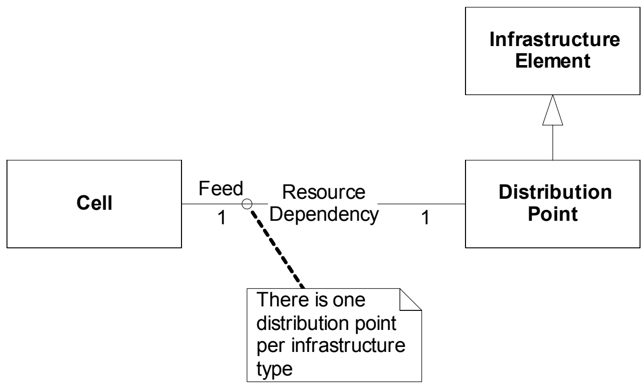

Figure 7: Distribution point: where resources flow from infrastructure to cells

3.4 Connecting diverse infrastructures

There are several kinds of physical interdependencies between infrastructures:

- *Dependent*: infrastructure A is connected and dependent on infrastructure B, meaning that if B is down, A is down. This is the case of a water pump depending on electrical power.
- *Dependent, with delay*: A is connected with B, and a failure of B will ultimately lead to a failure of A, over time. This is the case of a telephone equipment, with battery backup, depending on electrical power, but equipped with some battery back up (to hold a few hours) or with a generator (to hold for a few days).
- *Collocated*: this is a variant of dependent: two or more infrastructures are using the same physical space in a way that makes them fail simultaneously: a road bridge that carries a gas pipeline and a fiber optic are examples of such connections.

These connections are mutual properties of various infrastructures as shown in Figures 8 and 9.

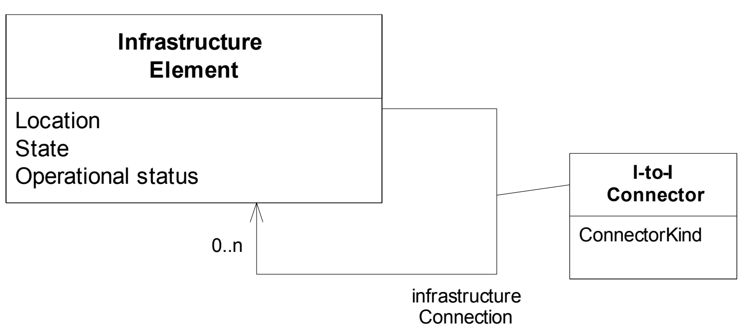

Figure 8: Physical connection between 2 different infrastructures (class diagram)

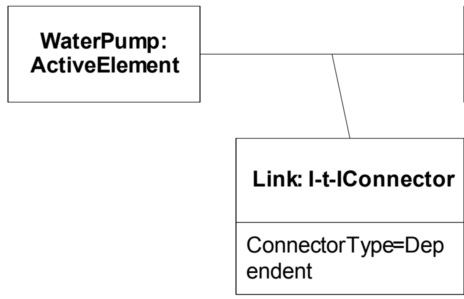

Figure 9: Example of a connection between 2 infrastructures (instance diagram)

There is a fourth case of interdependencies between infrastructures, with a *human-in-the-loop*. It does involve neither a physical connection nor a collocation, and we will describe it below in section 3.6.

3.5 External and disaster event

Disaster events are external events that "happen" and affect the state of cells and infrastructure elements shown in Figure 3 at the physical layer. As shown in Figure 10, they are characterized by their *nature* (flood, fire, earthquake,…), their *magnitude* and the *area* they affect (a model of the damage they inflict on various things). *Internal events* are associated with infrastructure elements or cell, that represent some spontaneous change of state (degradation or repair).

A disaster event, depending on its characteristics will instantaneously or over time change the wellness of cells or the state of infrastructure elements. An earthquake will kill people in cells near the epicenter, bring the wellness to low levels in adjacent cells, and over time affect the wellness of many other cells (lack of power, lack of food). The same earthquake will also immediately destroy some infrastructures (electrical tower, water pipes), with or without some cascading effect to adjacent elements, and more effects over time (see 'dependency with delay above').

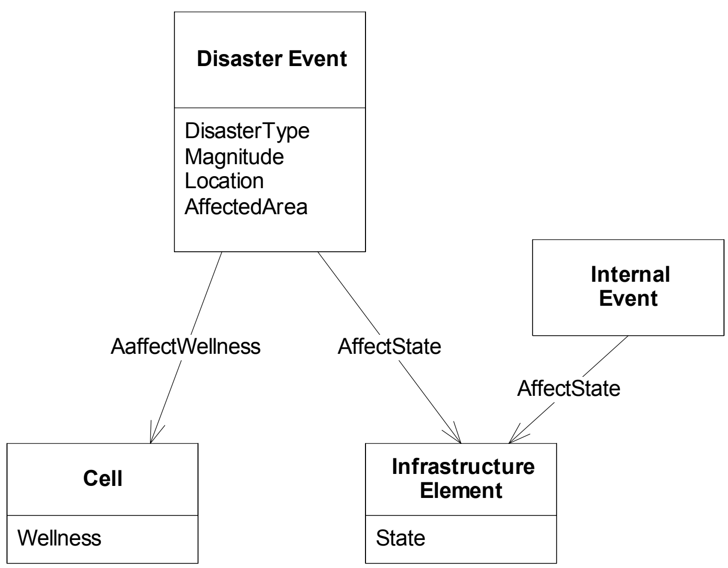

Figure 10: Disaster and other events: repairs, failures

3.6 Communication and coordination

The interdependencies between infrastructures that are physically interconnected can be modeled by classical means: including them in an incidence matrix, where we can describe the effect of element i on all elements j, over time, with various degrees of sophistication. These models have existed for years for electrical grids and can be extended to other similar infrastructures: road, water, sewer, etc. and infrastructure elements (infrastructures).

It is however difficult to represent the more subtle interdependencies between infrastructures, that involves a human-in-the-loop: someone residing in a region (or in control of some part of an infrastructure) needs to coordinate with other people in other regions (or in control of some other infrastructure segments). We use intelligent agents as the modeling paradigm for the actions of these people (Monu *et al.,* 2005) (See Figure 11).

A *conceptual agent* is an abstract entity that has *goals* (objective), *beliefs* (based on its observation of the world), and *states* (internal variables that can be compared with the goal). It can *observe* the surrounding environment, *reason* on how to bring it closer to its goal, and *act* accordingly. Some of the more sophisticated agents will also be able to *learn*, by observing the positive and negative effects on the discrepancy of previous attempts to satisfy their goals, and changing or adapting the strategies.

A conceptual agent can represent either a fully automated intelligent agent or a human being using some automated reasoning.. In the case where it is partially representing a human being, the various characteristics such as reasoning and learning will be human input during an execution or simulation.

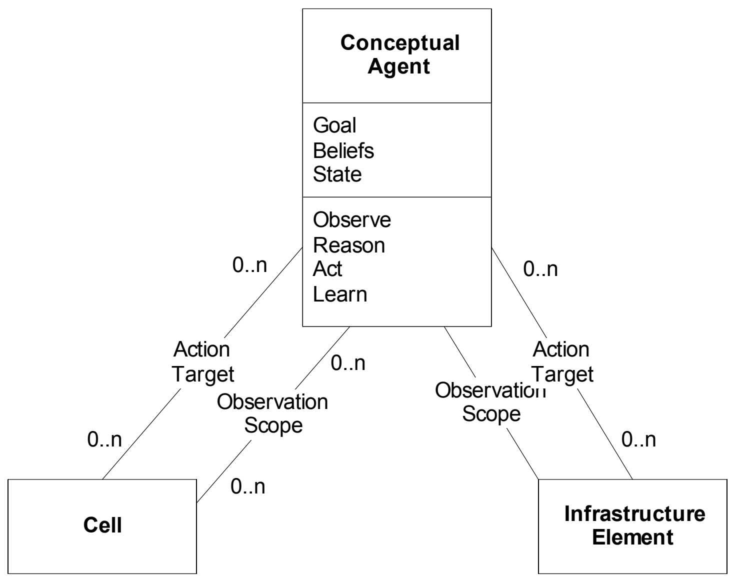

Figure 11: Conceptual agents observe and act onto cells (regions)

Conceptual agents are associated to entities in the physical layer: regions, cells, infrastructures and infrastructure elements. They constitute a third layer in the model: the communication and coordination layer (see Figure 4). They embody a third type of mutual properties between cells, between infrastructures, and cells and infrastructures: the social aspect.

We use conceptual agents to model *communication*; this is not the physical communication, such as the wiring and switches associated with a telephone call, which reside in the physical layer, but the information being exchanged between the entities associated with the agents. The agents convey information about their goals and the resources they need to satisfy their goals; they allow the diffusion of information. These agents also model *coordination*, that is, negotiation of mutually acceptable goals; resources or tactics that are required, tradeoffs, and compromises.

Depending on which entity in the physical layer it is associated with, conceptual agents have different goals and require different resources. For example, residential cell agents' goal is to maximize well-being of the people in the cell, economic cell agents pursue their economic activity, while infrastructure agents will restore their part of the infrastructure when it is not functioning. Figure 12 shows the complete structure of our model.

4. EVALUATION OF THE MODEL

We can evaluate our conceptual model, shown in Figure 12, from different perspectives. First, we have examined its intrinsic qualities, from traditional model evaluation in software engineering, based on principles such as abstraction, modularity, separation of concerns, generality, anticipation for change, rigor and formality (Ghezzi *et al.,* 2003).

Second, we performed an ontological evaluation using two criteria proposed by Wand and Weber (1993): ontological completeness and clarity. Ontological completeness can be defined as being able to represent all of the concepts that can be found in the domain of the model. Ontological clarity means that the models' constructs are not overloaded (one construct representing several different things), or redundant (several constructs modelling the same thing). Another problem is construct excess: when a model has a construct that does not correspond to its domain. While an in-depth analysis would be a research paper by itself, our current finding is that the concepts do correctly relate to each other and can express major concepts in the domain.

Third, we presented the model to industrial partners to obtain their feedback. We did this in a workshop where representatives of the electrical, telecommunication, transportation and water supply utilities in the lower mainland of British Columbia have attended and commented that the metamodel approach was the appropriate way forward.

We are also in the process of using the metamodel to analyze a small scale emergency management, in collaboration with our Campus and Community Planning department.

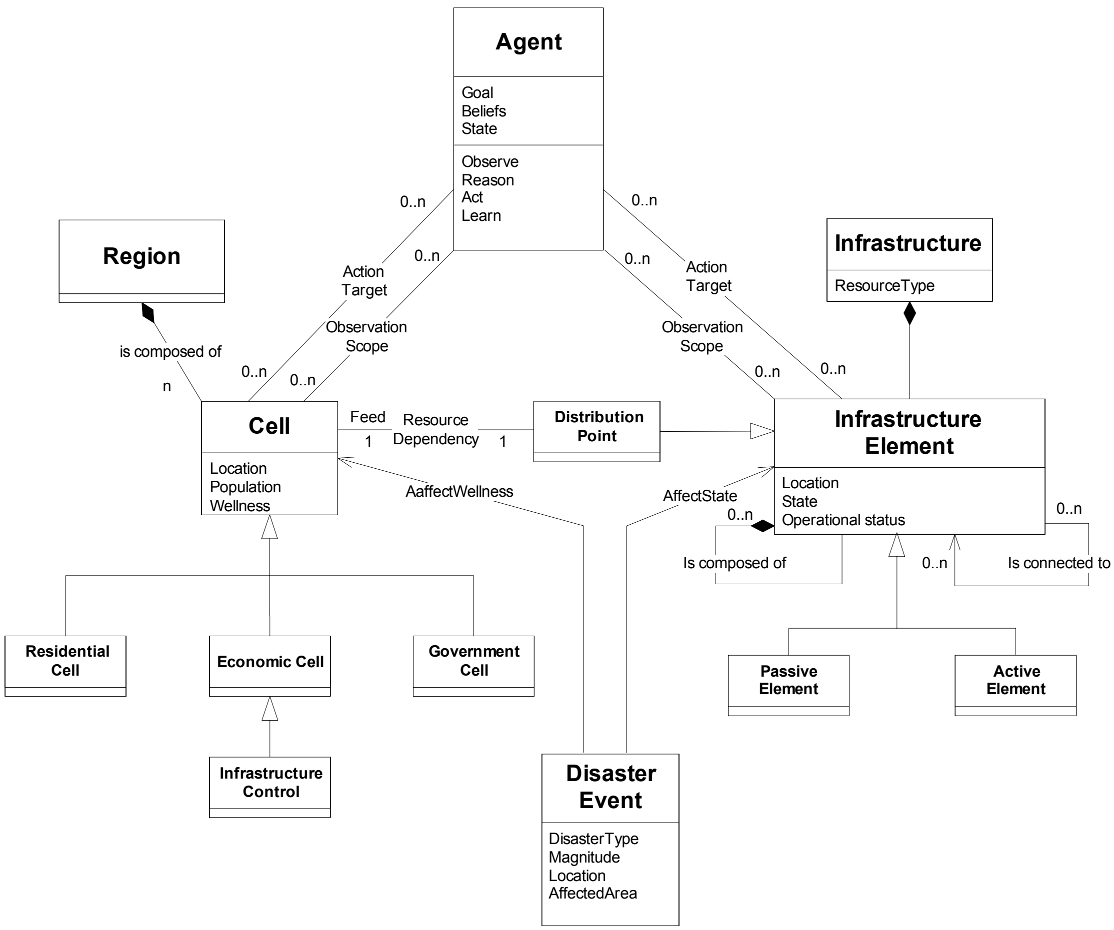

Figure 12: Overall model

Finally, we exploited the conceptual model to build tools for supporting emergency preparedness personnel, which is the topic of Section 5.

5. EXPLOITING THE MODEL

We are developing two tools using our model; a disaster simulator and a disaster querying system. Our perspective is to look at disasters from a human aspect and the tools we develop reflect this.

To explain what the tools can do, we will use a small example. A small town, called Lilton, has a disaster planning committee which wants to test its current disaster policy and implement a system to aid in disaster management if it were to occur. Using the Ontology from Figure 12, we created Lilton on Figure 13 with an economic cell: the hospital, a residential cell, three infrastructures with passive elements: pipes, and active elements: water pump. The three infrastructures are: water (coming from a reservoir through a pump), electricity (provided by the substation) and steam (generated at the powerhouse). There is a hospital and a residential area which need access to the infrastructures to function. The powerhouse and the water pump are collocated, meaning that if the power house looses power so does the water pump. Pipes (P1, P2, etc.) transport water and steam, while electricity lines (L1, L2, etc.) transport electricity. Only the hospital uses steam. Both electricity and water must be available at the power house to produce steam. Currently only the water infrastructure has put together a disaster management team in the town. There is a manager in the water planning facility who monitors the wellness of the hospital and the residential area. She is also responsible for informing the operator, located in the water operation facility, if there is anything wrong with the system. The responsibility of the operator is to fix only the water and steam infrastructure.

Two tools that can assist the town disaster management team are presented in the following two sections.

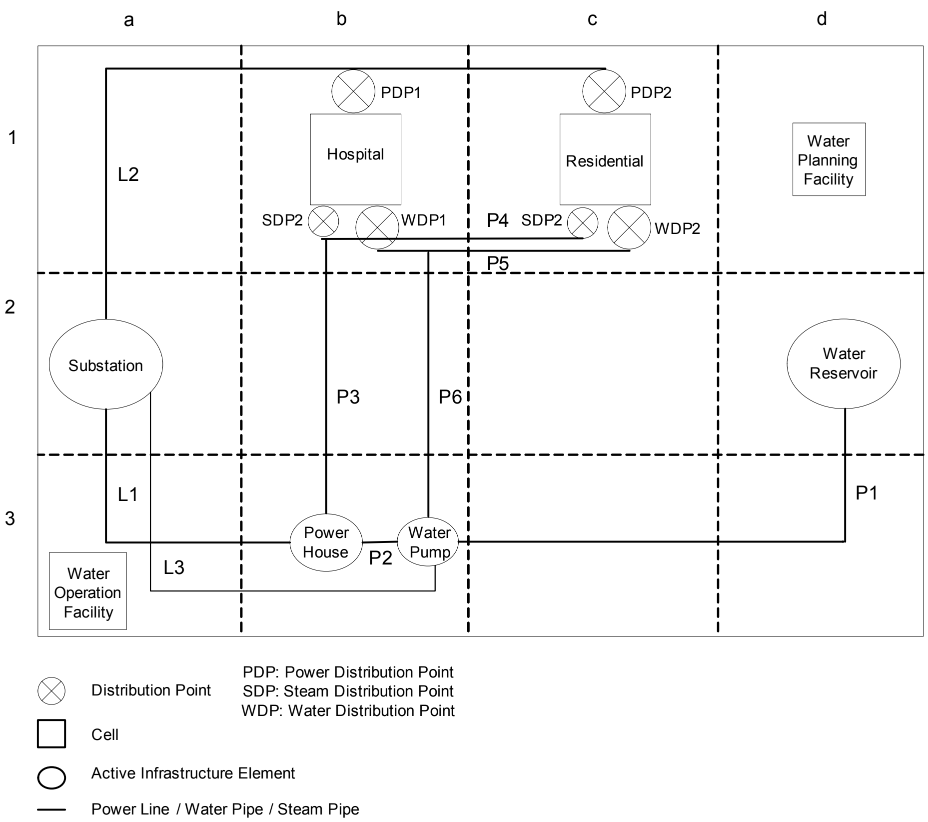

Figure 13: A map of Lilton, showing its 12 cells and 3 infrastructures

5.1. Agent Simulation

The purpose of the agent simulation is to "debug" established disaster policies. Usually these plans involve many different people and the interactions may be too complex to know how they are affected by different disasters. The agent simulation uses agents that represent actors in the disaster plan and uses a physical simulator to simulate the physical damage of the area. This is used to test out the assumptions of the policy and see where it goes wrong. This simulation cannot prove a plan to be perfect (there may be other variables that the modellers do not know about) but it can potentially detects problems in the plans.

The overall structure of a complete disaster simulator follows directly from the structure of our model (see Figure 14). It consists of four main components:

1. The *disaster visualization*: it shows a map of regions, cells, over which one can overlap the various infrastructures, and visualizes state of cells and operational status of infrastructures, over time. It is based on a GIS system that integrates all the data.
2. The *physical simulator*: similar to the simulators used in the power industry, it represents the state of all elements physically related: infrastructures and cells.
3. The *communication and coordination simulator*: based on conceptual agents, it models the human-in-the-loop

aspects; the focus is on the coordination of actions between various administrative entities, some responsible for infrastructures, some representing residential or simple economic cells.

4. The *disaster scripter*: this component allows the description of a disaster, either to analyze weaknesses in the infrastructures, to exercise some type of conceptual agents, or to visualize the gradual impact of a disaster, or even to capture what is known of a given disaster while it is happening, to use the simulator as an aid to support decision.

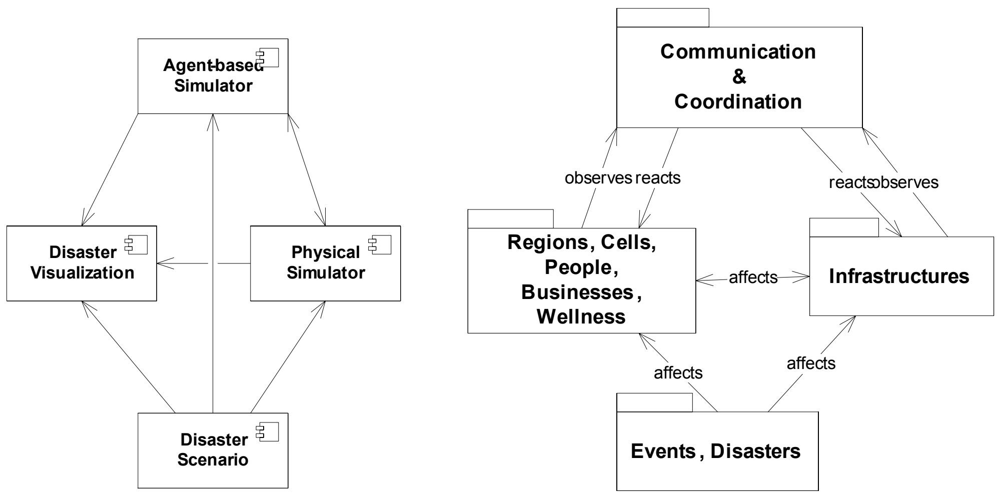

Figure 14: The structure of the simulator is matching the model structure

Let us examine a disaster policy from Lilton disaster plan, which involves the disaster manager and the water, steam and electricity operators (see Figure 15). The manager monitors the wellness of the residential area and hospital. When she sees something wrong she must decide who to contact to fix it. The operator of each infrastructure waits for a call from the Manager to enquire if their infrastructure is the one that is affected. Once contacted, the operator then investigates the element it believes is the most likely cause.

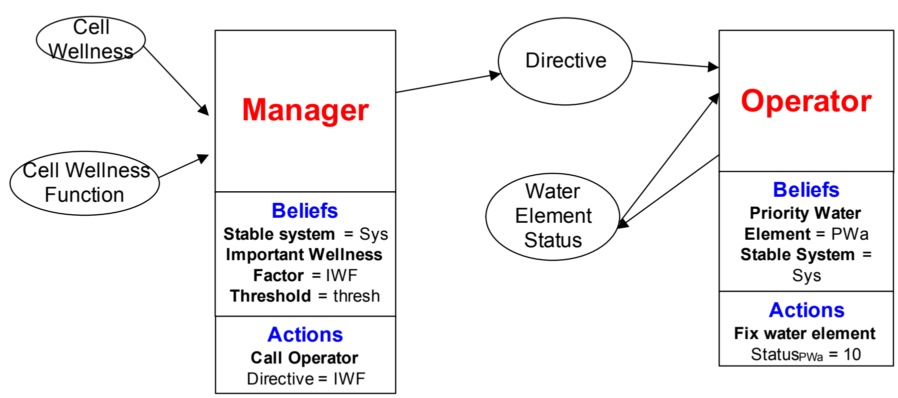

Figure 15: Agent Diagram

The simulation gives us several statistics; for instance, the time it takes for the system to recover, or which areas are most affected. This in turn is used to evaluate the proposed policy and also used as performance measures for each policy in the plan. Note however that our tool does not optimize the plan for the user. It simply plays out the assumptions made. To fix a bad plan, the user must decide what changes to make to the policy and test it.

Currently, we are working on incorporating the agent diagrams shown in Figure 15 into a disaster simulation. Previous work shows that this can be done. In Monu *et al.* (2005), the authors used the same modelling language to create a simulator using the agent platform called Netlogo (Wilensky, 1999). The environment merges object-oriented programming languages (Java) with agent specific commands and operations (Tisue & Wilensky, 2004). Just like in object-oriented languages, each "object" in Netlogo can have a unique set of variables. Like in conceptual agents, Netlogo differentiates between system and agent variables, which are declared separately. However, Netlogo does not keep track of beliefs or procedures, so they were represented in Netlogo code as generic variables of the agent. However beliefs and procedures can be identified because of the structure of the code.

The agent simulation is currently under construction and will be made to work with the physical simulation as shown in Figure 14, where the physical simulator will be connected to a database of real data but is beyond the scope of this paper to elaborate them. To operate the simulation the user will need to model infrastructure and the buildings supported by it. They will also need to create the agents that enact parts of the disaster plan. Specifically the simulation needs to know what kind of actions the agents will take when certain events occur in the world. Once these agents are programmed the agent simulation can interface with the physical simulation and the consequences of the plan can be shown.

5.2 Disaster Querying System

A second tool based on our model framework is the Disaster Querying System (DQUEST), whose purpose is to help the operators to find the causes of service interruption during a disaster. There might be situations where due to communication disruption, the operators are isolated from outside world and the information they receive is incomplete and uncertain. Under such situations, DQUEST helps the operators to find the most likely action with existing evidence and assumptions they make about uncertain or incomplete data.

Again the overall structure of DQUEST follows directly from the structure of our model (see Figure 16). The information in DQUEST can be manipulated by the operator or an external system such as Physical Simulator. Any changes to DQUEST or the simulator are reflected in Disaster Visualization tool.

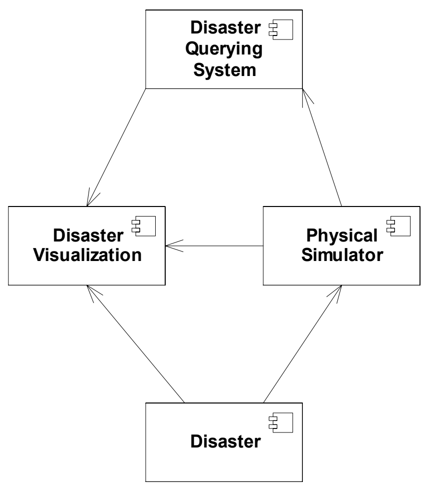

Figure 16: Conceptual model of DQUEST

Back to Lilton again, DQUEST holds the information about the physical elements of the infrastructure and their interdependencies. Using the model in Figure 12 as our database schema, Figure 17 shows the table structures capturing the information of physical elements in Lilton. Each table represents a physical element of the water or power infrastructure. Element attributes have a “confidence level” attached to them: a value between 0 and 1 which represents the degree of belief or confidence on that value. Interdependency table incorporates the interdependencies between the physical elements in Lilton: functional dependency, co-location, or simply physical connection.

DQUEST also contains information on the human aspects of Lilton: roles and responsibilities of human agents and their connections or relationships, or the resources they need to accomplish their duties (see Figure 18).

Cell

ID	Type	Location : CL*	Population : CL	Wellness : CL
Residential	Residential	(1,c) : 1	10 : 1	10 : .9
Hospital	Economic	(1,b) : 1	5 : 1	10 : 1
…				

*** : Confidence Level**

Water Reservoir

ID	Type	Location : CL	Capacity : CL	Status : CL	Operational Status : CL
Water Reservoir	Water Storage	(2,d) : 1	2000(m3) : 1	5 : 1	5 : 1

Water Pump

ID	Type	Location : CL	Capacity : CL	Status : CL	Operational Status : CL
Water Pump	Water Pump	(3,b) : 1	500(m2) : 1	5 : 1	5 : 1

Pipe

ID	Type	Location : CL	Length : CL	Status : CL	Operational Status : CL
P1	Water Pipe	(2–3,b–c–d) : 1	1500 (m) : 1	5 : 1	5 : 1
P2	Water Pipe	(3,b) : 1	10 (m) : 1	5 : 1	5 : .7
…					

Substation

ID	Type	Location : CL	Input-Output : CL	Status : CL	Operational Status : CL
Substation	X	(2, a) : 1	(5000 ,110) : 1	5 : 1	5 : 1

Line

ID	Type	Location : CL	Length : CL	Status : CL	Operational Status : CL
…					

Power House

ID	Type	Location : CL	Capacity : CL	Status : CL	Operational Status : CL
Power House	X	(3,b) : 1	7200 : 1	5 : 1	5 : .9

Distribution Point

ID	Location	Status : CL	Operational Status : CL
PDP1	(1,b)	5 : 1	5 : 1
…			

Event

ID	Type	Location	Severity	Duration
E1	Earthquake	Region r	Medium	1 (minute)

Interdependency

Element 1	Element 2	Interdependency : CL
Water Reservoir	P1	Connected : 1
Water Pump	P1	Connected : 1
Water Pump	P1	Functional : 1
Water Pump	P2	Connected : .9
Power House	P2	Functional : 1
Power House	P2	Connected : 1
Power House	L1	Connected : 1
Power House	Water Pump	Co-located : .8
…		

Figure 17: Physical Layer Data

Personnel

ID	Role	Work Address : CL	Home Address : CL	Contact No. : CL
Manager 1	Manager	#402 - 1550 West Mall : 1	...	604-228-0000 : 1
Operator 1	Operator	#102 - 2550 Main Mall : 1		604-228-0001 : .6
Operator 2	Operator	#101 - 2550 Main Mall : .9		604-228-0002 : 1

Supply

ID	Type	Status : CL
Truck1	Truck	Available : 1
Truck2	Truck	Available : .5

Responsibility

Personnel ID	Linked To : CL	Action : CL
Manager 1	Operator 1 : 1	Call : 1
Operator 1	Truck1 : 1	Allocate : 1
Operator 1	Truck2 : 1	Allocate : 1

Figure 18: Human Layer Data

Ideally, the information in the database reflects the real world states, but during a disaster the confidence levels of data in the database decrease. When receiving a new problem report, the operator queries the database to obtain complementary information about the problem and find an appropriate way to approach it. For example, if he is informed that cell 'b3' is without water, he may run queries such as:

- *What physical elements do provide water to the given cell?*
- *What other elements are dependent on element 'a'?*

to progressively narrow down the possible causes of this problem.

We use a Bayesian Network (BN) (Goldenberg and Moore, 2005) to visualize the information in the database and assist the decision process (see Figure 19).

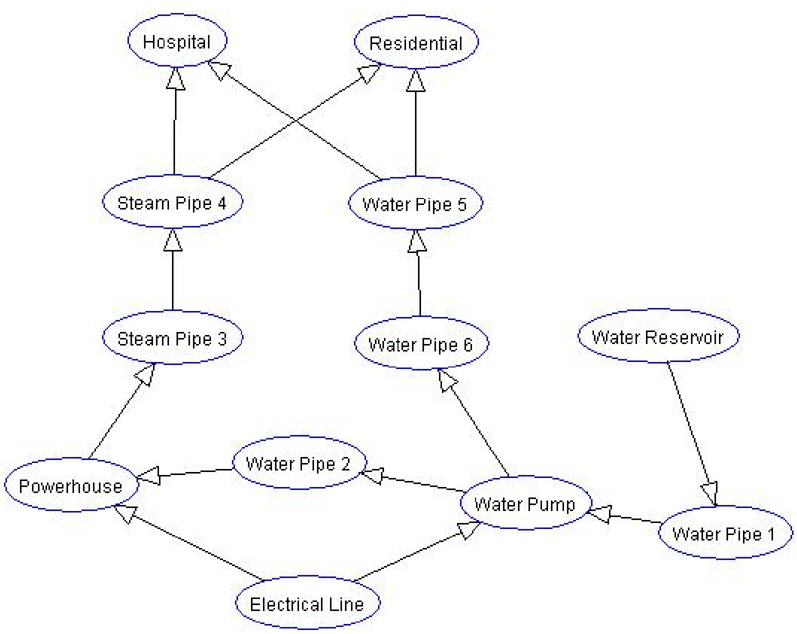

Figure 19: Bayesian Network for Lilton infrastructures

The nodes are the physical elements or cells. The arcs show the functional dependency. The prior states of nodes are specified in Figure 20.

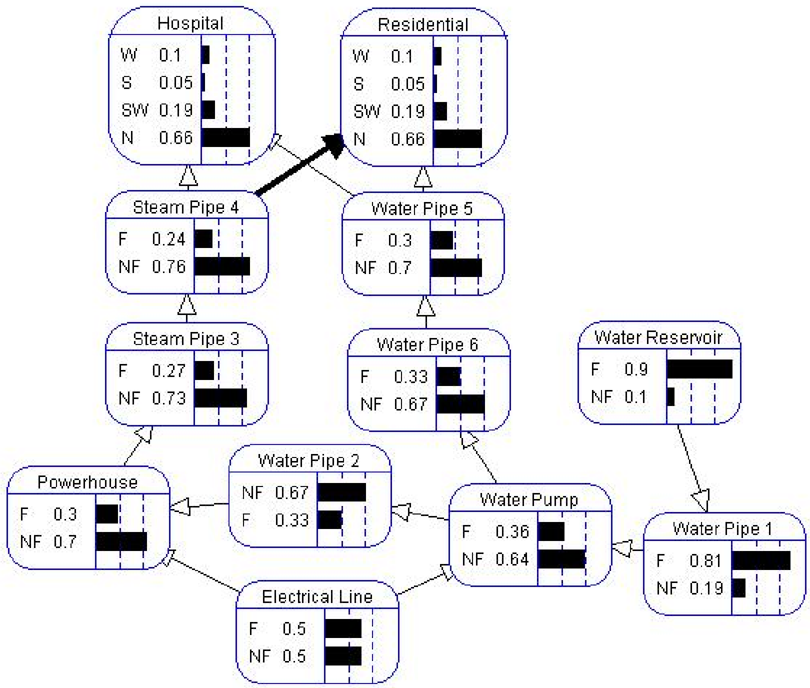

Figure 20: Prior states of the nodes

Based on new observations, the operator changes the state of a node and the BN calculates the new states of interdependent nodes: the BN traces the effect observed back to its probable causes. Here are examples of samples of queries the operator may run:

- *Knowing cells 'b' and 'c' are out of water, what elements are likely to be the cause?*
- *What is the impact of dynamically adding a new pipe?*
- *What is the likelihood of increasing the wellness of 'b' by fixing 'a'?*

Figure 21 illustrates the first query: the operator is informed that Hospital and Residential cells are out of water. He sets the status of both cells to 'S' meaning "Steam Only". The BN calculates the new states of nodes and concludes that certainly Water Pipe 5 has no water.

In terms of implementing the Bayesian network tool, all that is needed is information about the physical world. As stated before, the tool is used to aid individuals in learning about vulnerabilities in infrastructure. What the user will need to first do is model the infrastructure. This is done by creating nodes for each part of the infrastructure, status for each node, and causal links between them. Once the links have been created conditional probabilities for each node must be entered to complete the model of the infrastructure. However the infrastructure does not have to be represented in great detail. For example, the water department may know nothing about the electrical grid but guess that if an earthquake were to occur that there is a 60% chance that the grid will go down. To represent this they can create a node called "power grid" that has a 60% chance of failing.

5.3 Other Possible Applications

The model is currently being used as a way to inform our construction of a simulation. Inform means to act as a guide to integrate various disparate parts of a larger project (including the physical simulator, a database, and visualization of simulations). The model links those in the larger project group interested in physical infrastructure with those interested in the human element through distribution points. The model also specifies how agents can affect the infrastructure. The model can also be used to improve existing tools by analysing the interaction between tool's components. Just like Chakrabarty and Mendoça (2005), this work could be used to develop design principles for multi infrastructure disaster simulations. For example, in the RoboCup Rescue simulator there is infrastructure (roads), agents and buildings. However the platform allows modules to be plugged into the simulation which can be simulation of disaster events, agent behaviours, or infrastructure recovery (RoboCup Rescue Technical Committee, 2000).

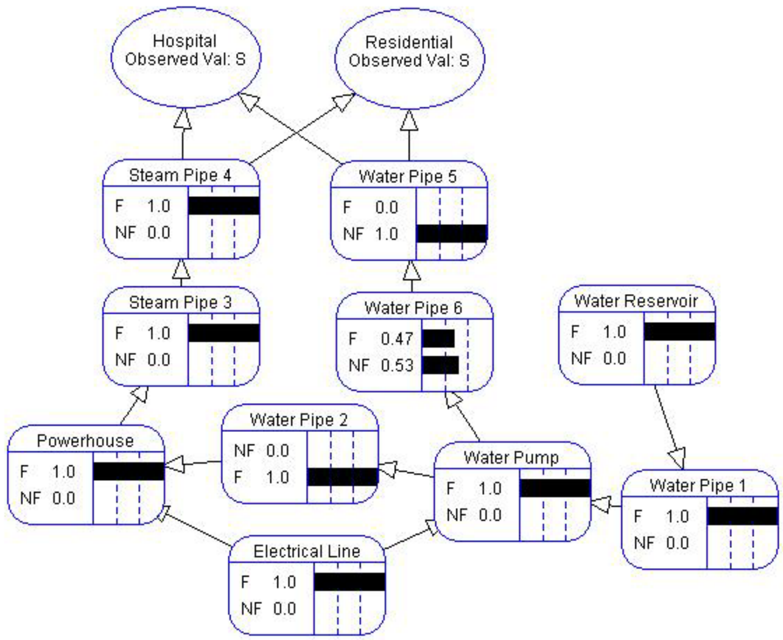

Figure 21: New states of the nodes

Our ontology could be used to create guidelines for writing modules which work together in RoboCup. For instance, if in a banking system module the kernel would need to know which cells (buildings) are economic cells and which are residential. The destruction of a banking system would directly affect the former but not the later. Also the differentiation between active and passive elements in an infrastructure would be important when writing a module of an infrastructure during a disaster. An active element usually needs something (power, people) to function and a simulation that takes this into account can show an infrastructure that is not physically damaged, but can still not function because of a lack of requisite resources. A more in depth analysis of the tool using our ontology could lead to more design rules.

6. CONCLUSION

We have designed a metamodel of disaster-related concepts to assist us in the building of simulators to support emergency preparedness and response. We discovered that the research landscape exhibits a patchwork of partial models, not well-integrated, with inconsistent terminology. Our metamodel is a start on the path towards the unification of the terminology and it allows sharpening the definition of terms and in particular their semantic relationships. The model does not yet explore, for example, the social constructs that sociologists use to conceptualize disasters from their vantage point, and how to relate them to our concept of wellness.

This is not merely YAOYAD (yet-another-ontology-for-yet-another-domain); this ontology spans multiple domains from geography, to technology, to business, to health and social issues, and deals simultaneously with several layers: physical, social, and external events. We believe we have tackled these two dimensions without introducing excessive complexity. The feedback we got from industry has been good, as we start to apply this model and the tools to a small scale real-world test case (a large campus) to assess both its usefulness and limitations.

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