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INTEGRATED HAZARD ANALYSIS METHODOLOGY TO STUDY INTERDEPENDENCIES AMONG CRITICAL INFRASTRUCTURES

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ABSTRACT

The system of critical infrastructures (CIs) constitutes the backbone of modern societies. During large disasters the situation is very different from normal life because multiple infrastructures are affected simultaneously, and unless they coordinate each other's actions, the overall response process may suffer serious stalls. This paper will describe a research project conducted at the University of British Columbia (UBC) during the last three years to develop a new integrated hazard analysis methodology to study interdependencies among critical infrastructures.

The I2Sim simulation environment, developed in the project, provides a multi-system representation of all infrastructures involved in the disaster response at multiple hierarchical levels of the global system. The flow of resources between CIs is explicitly represented without revealing their internal details. In addition to its real-time decision support capabilities, the mathematical formulation of I2Sim permits the analysis and discovery of vulnerable points in the system as well as gaps in policies and procedures. The purpose of the system is to ensure that at any given moment, and under natural or man-made hazard events, the resources will be targeted to the most vulnerable areas of critical infrastructure.

The methodology developed was used for the identification of interdependencies among critical infrastructure. The results will benefit infrastructure operators, emergency response planners, regional planners, policy and decision makers, as well as educators.

Introduction

As the rate and severity of natural and man-made disasters' have increased, so has the possibility that disruption of Critical Infrastructure could result in prolonged loss of essential services.

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The task for local and global authorities is to establish an action plan to guide the identification of risks, the implementation of protective safety measures, and the proper and effective response to disruptions of critical infrastructure.

The ultimate goal of this research is to develop a methodology that helps strengthening the resiliency of critical infrastructure. Seismic Risk Assessment methodology will be used as a benchmark. This methodology will be used for the identification of interdependencies among critical infrastructure. In this research a “study space” would be disassembled in a finite number of physical layers (human and physical), also known as critical infrastructure systems. Risks will be estimated separately, and interdependencies will be assessed superimposing the layers one by one, (Martí et al, 2006; Martí et al, 2008; UBC-JIIRP, 2009 and Juárez García, 2010).

The general objectives of the UBC-JIIRP research were to: 1) develop a methodology for evaluating risk for natural and man-made hazards that helps discovering vulnerabilities in order to strengthen the resiliency of critical infrastructure systems; 2) identify interdependencies among critical infrastructure and obtain Interdependency Indices for Critical Infrastructure systems; 3) provide documentation on how the risk estimates should be implemented by UBC-JIIRP project; and 4) implementation of results, assessments, outcomes for the simulator I2SIM. In this paper a general discussion of the methodology and results will be presented for an earthquake Scenario of Instrumental Intensity IX. The objectives and details of the research are compiled in (JIIRP-UBC, 2008 and Juárez, 2009); the latter is still in progress.

Background

Previous work on Seismic Risk Assessment in British Columbia

The University of British Columbia developed a classification system for buildings in British Columbia. A comprehensive building database was assembled and the expected damage was estimated using damage probability matrices. Nonstructural component and building content damage probability matrices were also developed. This methodology was applied to urban regions within the Vancouver Lower Mainland; Bell, 1998; Blanquera, 1999 and Bell, 1998.

In 2001 and 2005, the potential damage and subsequent monetary losses were estimated from seismic shaking for other regions within British Columbia. Structural damage was estimated using the damage probability matrices, and the results were mapped on a block by block basis using GIS software. Nonstructural damage and monetary losses were also estimated for the study areas; Onur, 2001; and Onur, Ventura and Finn, 2005.

All the previous works were focused on the building infrastructure and non structural components; in this research lifeline systems were also considered for identifying risks in Critical Infrastructure (CI) systems. Seismic Risk Assessment shall be performed on an extended set of Lifeline Systems within the studied case. Furthermore, the consequences of the damages in every CI will be assessed, and how these damages and consequences affect other systems. Interdependencies will be evaluated and ranked for every Lifeline System, (UBC-JIIRP, 2008; Ventura et al, 2008 and Juárez García, 2010).

The Joint Infrastructure Interdependencies Research Program (JIIRP)

JIIRP is part of an effort by the Government of Canada to fund research to develop innovative ways to mitigate large disaster situations. Six universities across Canada were involved. The University of British Columbia (UBC) studied decision making for critical linkage in infrastructure networks.

Infrastructure Interdependencies Simulator

UBC-JIIRP aims to model the real time effects of a disaster and identify the interdependencies among critical infrastructure networks. There are six principal components of the projects architecture: the physical layers, damage assessment, human layers, database (I2DB), the infrastructure interdependencies simulator (I2Sim) and visualization. In order to simulate a disaster event, it is necessary to determine the expected level of damage sustained by the infrastructure networks as the result of the disaster.

The damage assessment module involves the estimation of physical damage to the component, the number of casualties, the amount of economic loss and the loss of function that results from this damage. The data generated in the human and physical layers are aggregated into a database (I2DB). This database provides a common platform for data storage and is set up to feed the data to the simulator directly and receive the output of the simulation.

The simulator model is made up of three primary components: tokens, channels, cells and controls. The basic function of critical infrastructures is to transfer resources (tokens) from the location where the resources are produced or stored (cell 1) to the location where they are utilized or accumulated (cell 2) through transportation channels. Controls (distributor and aggregator units) model the interface between the physical and the decisions making layers. Distributors provide the links between the physical distribution of output resources and the human layer of decision makers. The purpose of the system is to ensure that at any given moment, and under natural or man-made hazard events, the resources (tokens) will be targeted to the most vulnerable areas of critical infrastructure, (Marti, et al, 2008 and UBC-JIIRP, 2008).

UBC Test Case

The University of British Columbia Point Grey campus was modeled as a case study, as an implementation of the simulator methodology. The geographical location, infrastructure complexity, and the diversity of its population made it an ideal test case to develop, assess and validate I2Sim. The University has a population of approximately 10,000 full time residents and 47, 000 transitory occupants and most of the utility systems are managed internally. As such, it shares many of the attributes of a small city; an earthquake scenario was selected as the disaster to be simulated in the test case.

Methodology

Along the UBC-JIIRP project a 16 steps methodology was proposed to arrive to a proper model of a study space. These guidelines along with the methodology will help revealing second order and higher interdependencies. Two contributions are highlighted for this project and other Multi Hazard Risk Assessment projects, Juárez García, 2010 and UBC-JIIRP, 2009:

1. A way of measuring interdependencies among Critical Infrastructure systems (CIs) through Seismic Risk Assessment. A way to measure Single and Global Interdependencies as well as the Overall Resiliency of one system. These calculations were used as starting points for the measurement of the resiliency of the system throughout the recovery time. In this research the following measurements were used to arrive to Interdependencies and Resiliency calculations:

    a. The damage estimation of structures and non-structural components (NSCs) of critical stations as parts of CI systems
    b. The overall functionality condition of critical stations
    c. The functionality estimation of CIs
    d. The Single Interdependency
    e. The Global Interdependency of the region
    f. The Resiliency Curve of the system through a lapse of time
    g. The Interdependency Index and the Importance Factor of every system

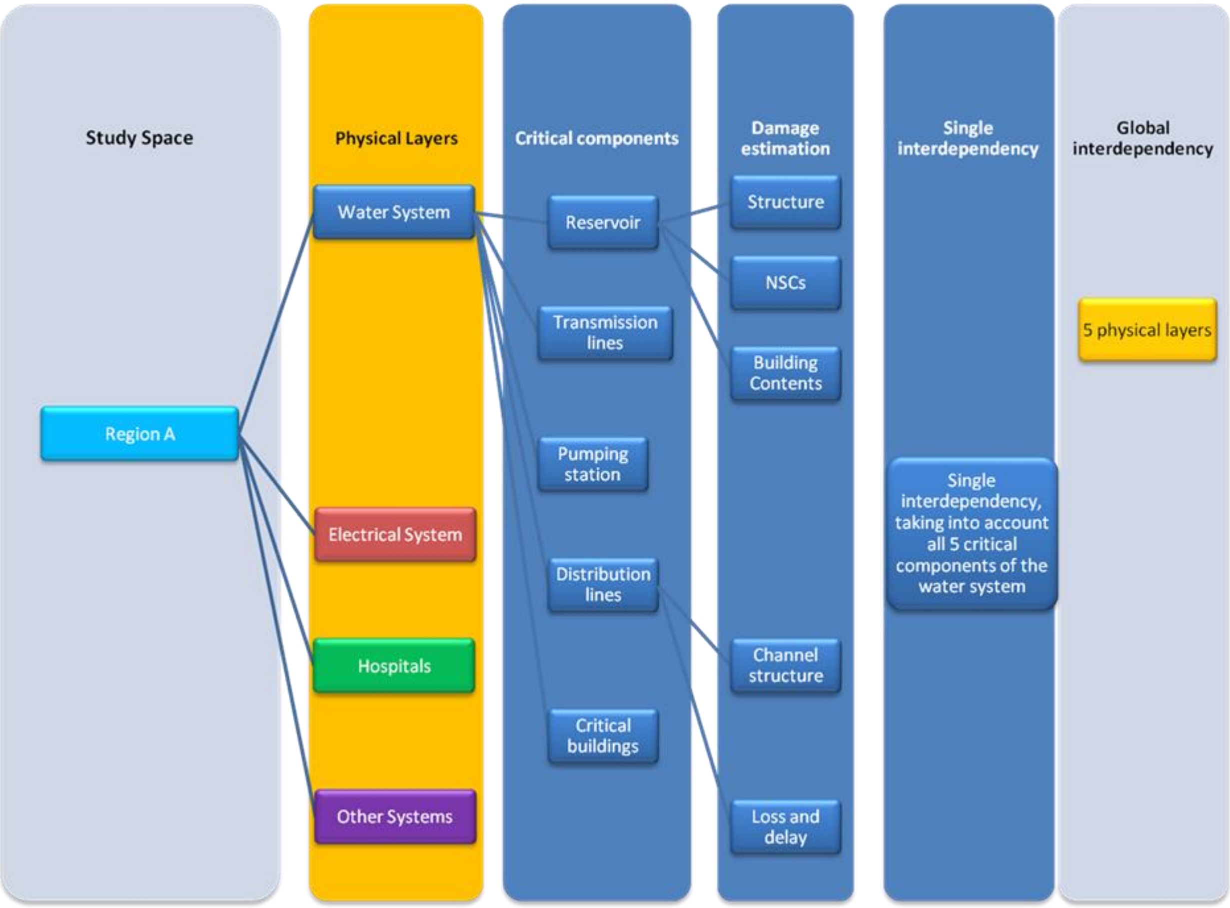

Figure 1. Single and Global Interdependency concept

Figure 1shows a study space (region A) with 3 Critical Infrastructure systems (Water, Electricity and a Hospital) that are needed to maintain normal life conditions, along with one block representing “other systems”. It also shows five components of the Water System, three of them are specialized buildings, and the other two are pipelines. All of them will define the functionality conditions of the water system. Figure 1 also emphasizes that damage estimation is different for buildings (cells) and the corresponding pipelines (channels). Nevertheless, once the damage estimation has been obtained, then all 5 components are weighted and they will define the overall functional condition of the water system, which is defined here as Single Interdependency. The Single Interdependency is obtained for all the physical layers of Region A. If Single Interdependency is defined, and then weighted and combined, then the overall functionality condition of region A can be defined as well, this research defines it as Global Interdependency.

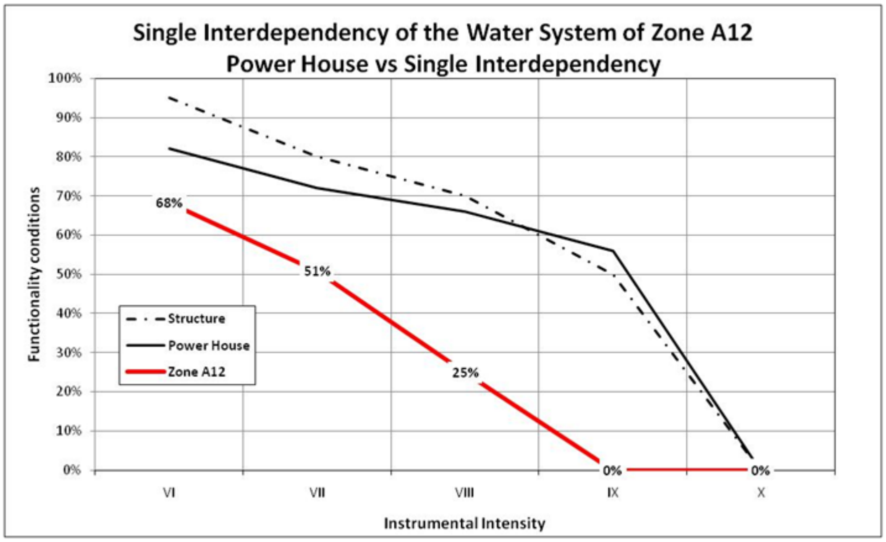

Figure 2. Single Interdependency of the Water System

Figure 2 shows the Single Interdependency of the Water System at region A12; the structure, the behaviour of the structure along with non-structural components, and the performance of all the components of the water system are shown. It is evident that the seismic performance of structure of the Power House is closely related to the equipment, furniture and pipelines inside the building. For an Instrumental Intensity VI, the structure has 95% of functionality, but due to non-structural behaviour the functionality conditions may drop to 82%; but if we consider all the elements that are needed to distribute water from the reservoir up to region A12, then the remaining functionality conditions will be close to 70%. Figure 2 also shows that water service in the region is possible after instrumental intensity earthquakes VI to VIII, even though water tap advisory might be issued by the managers of this region. For an Instrumental Intensity IX and above the water service will be compromised unless preventive actions are taken to improve their functionality conditions.

The Critical Infrastructure System resiliency of the whole region can be calculated using the Single and Global Interdependencies. Figure 3 shows the average value of the Global Interdependencies, of course this resiliency can be measured according to the objective functions of the region. Let's assume that the average value is enough to measure the whole system resiliency; this means that the system will be losing functionality conditions (77%, 65%, 44%, 26%, 11% and non-functional) for Instrumental Intensities: VI, VII, VIII, IX, X and XI. It is noticeable how related the resiliency of the system is to the Hospital functional conditions. This fact emphasizes that some key Critical Infrastructure buildings that utilize most of the systems of the region can be assumed as monitors of the system's resiliency. During the process of this research, through the interviews with the managers of the utilities, they often referred that Hospital or Health care services noticed a low in the pressure of the water system, or the lack of steam or gas.

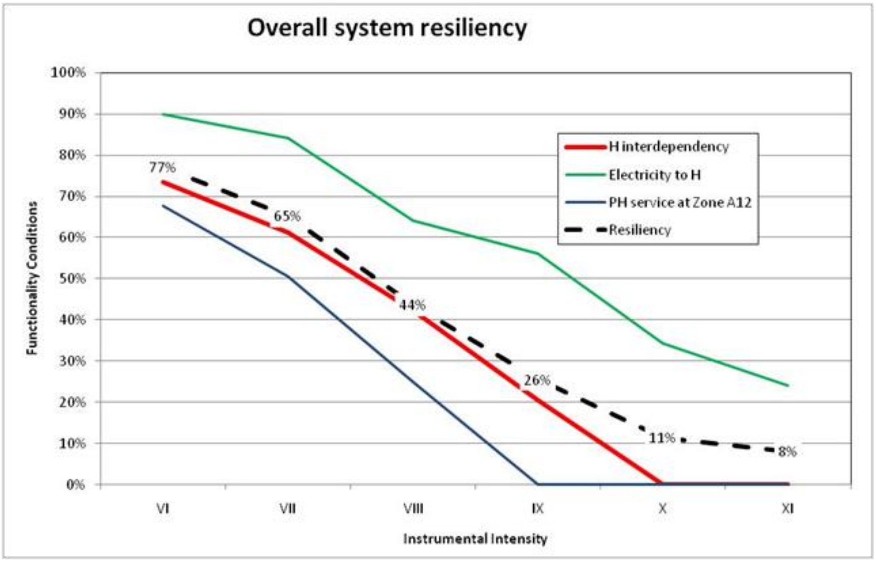

Figure 3. Overall system resiliency

2. **Define Human Readable Tables HRTs and operating modes.**
   The damage assessment provides the functionality condition of critical buildings (cells), losses in pipelines or roads (channels), and the overall functionality condition of lifeline systems after the event has occurred.

With the information gathered and developed with the damage assessment, then it is possible to translate the behavior of the critical lifelines into Human Readable Tables (HRTs) and Operating Mode (OMs) that can be used in the model of the "study space" in the simulator I2Sim. All information produced in the Damage Assessment Module (I2DAM) is stored in the Infrastructure Database (I2DB). Once all the information is stored in HRTs, then i2Sim simulations will commence, and the dynamically evolving process of the disaster can be then exercised. This risk level should be evaluated by policy makers and government officials to determine if the level is acceptable), details of the project architecture can be find in (UBC-JIIRP, 2009 and Juárez García, 2010).

UBC-I2Sim Model

Cell and channel representation

In order to capture the interdependencies of infrastructures with the associated impact to casualties, the campus cells were aggregated in the most relevant functional groups. The following cells were considered in this analysis: Residences, Stadium, President Office, IT building, First responders building, Parkades, Hospital, Power Substation, Water Station and Steam Station. For instance, four residence zones were created with common functionality buildings sharing a geographical area: Acadia: 100 buildings, South: 38 buildings, West: 11 buildings and North: 32 residence buildings. Different factors were introduced in the residence model cell, such as population per residence, electrical power and Steam consumption, First responders available per residence, number of gates for evacuation, among others. The representation of the I2Sim residence model is shown below, Figure 4:

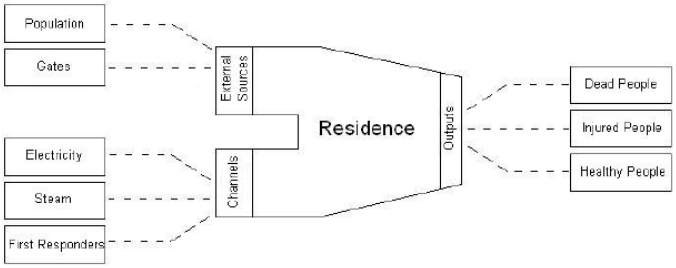

Figure 4. Residence cell model.

The I2Sim model is able to represent the dynamics changes in the token, deliverables and objectives requirements during the different stages of the event. For instance, in the case of the Hospital cell, two operational modes: the normal and emergency were considered in order to better represent the changing requirements from normal to emergency stage, Figure 5. The operation modes have a direct influence in the amount of tokens required, as well as in the operation priorities and availability of servicing channels. These are dependent on the operation status of the channels and cells feeding the hospital cell. The simulation tool provides a visual representation of the resulting physical mode which represents how the building is damaged and how its operability is affected. The simulation cell mode status indicates the main token constraint contributing to the reduction of operability. The cell model used a color scheme to easily identify the percentage of damage or the percentage of operability. Figure 6 shows the basic parameters available to the user to visualize the evolution of a cell operation.

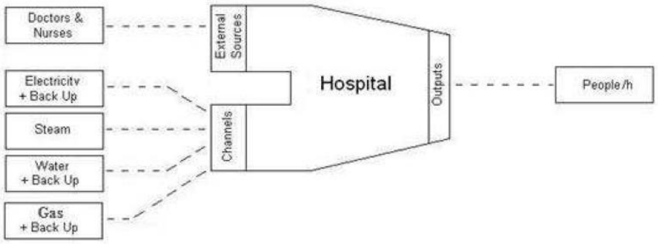

Figure 5. Hospital cell model.

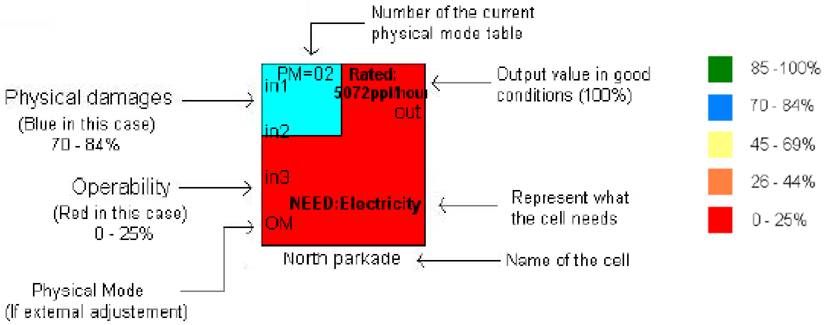

Figure 6. Cell block representation and color operability scale.

Interdependency among critical infrastructure (water system and buildings)
The general information of the earthquake scenario is: a) Location UBC Point Grey Campus; b) Time: 2 pm and; c) Instrumental Intensity IX. Figure 7 shows the interdependency of both systems, the trunk line providing water to the water station has an accumulated loss of 8 %, but the water station is non-functional due to the extended damage to its structure and non structural components. A more realistic situation would be that the entire UBC campus will be suffering from a shortage of water and will remain non-functional. These types of maps are referred as Interdependency Mapping in this research.

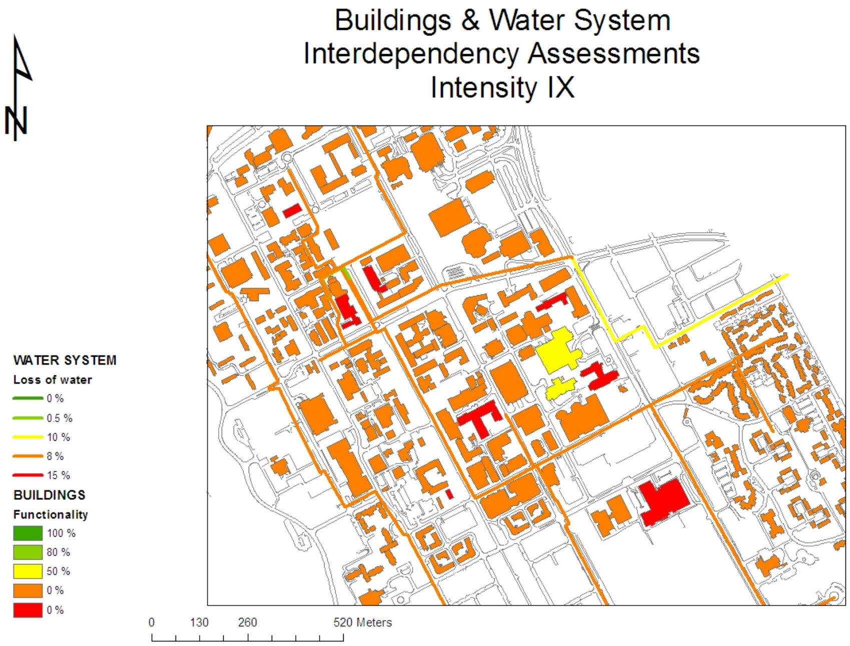

Figure 7. Functionality conditions with interdependencies, water system and buildings

Details and more analysis and examples on interdependencies can be found in (Juárez García, 2010 and UBC-JIIRP, 2009).

Multiple Infrastructure Interdependencies Simulation, UBC Test Case

In this analysis, multiple UBC infrastructures were simulated using I2Sim to integrate the structural damage of buildings and road assessment for a given earthquake. The integration of expected structural damage, density of population, and operational interdependencies of infrastructures provide a more accurate representation of the consequences of the event focused on a particular aspect. In this study the focus was put in the casualties. The event was simulated at different campus operation times to analyze and visualize the interdependencies and sensitivities of particular buildings and infrastructures with the associated damage and the number of casualties.

Simulation results

After having all the UBC critical infrastructures, cells and channels incorporated in the model, I2Sim simulated the entire system and analyzed their evolution after an Instrumental Intensity IX earthquake. The simulation was focused on three different operation times and the amount of casualties and the flow of arrival and treatment delivered at the hospital cell.

In Figure 8, the blue curves represent the number of people per hour arriving at the hospital, while the numbers of treated people are represented by the red curves. The green curves represent the numbers of people in the waiting room, which is in fact a delay that can be exacerbated by the operation condition of the cell based on the damage suffered to the servicing infrastructures and limited tokens.

In this case, the difference observed in the amount of people arriving at ER, and its operation performance is affected by the distribution of people and the damage expected in buildings with higher concentration of people.

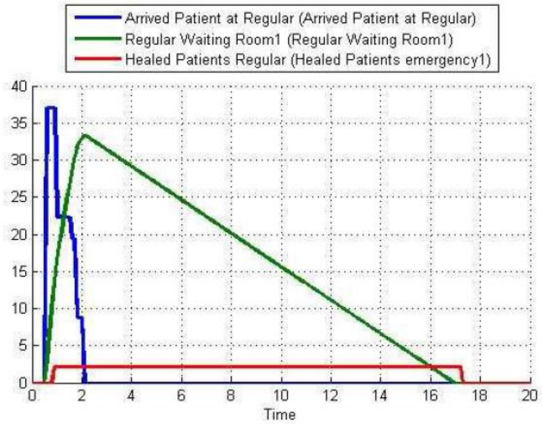

Figure 8. Hospital cell emergency room after an event at 5 pm.

Conclusions

The outcomes of each individual damage assessment do not show the complexity of interdependencies of the systems within a “study space”. But when they are arranged and the interdependencies are taken into account, all of a sudden they are very important; and will help develop better action plans, in order to reduce vulnerabilities, or to decide where to put more resources in the critical infrastructures that need more attention. This example of interdependencies can be observed dynamically through the i2Sim Simulator that will produce static and dynamic visualization tools; so that operators of the CIs could see the outcomes in real time.

One of the contributions of this research is to implement the methodology in the i2Sim Simulator, so that this tool can be used to assess interdependencies of Critical Infrastructures, during an emergency event (multi-hazard event).

I2Sim is a powerful tool that will allow the owner of the “study space” to investigate possible outcomes, vulnerabilities, interdependencies among Critical Infrastructure, so that consequences can be minimized.

Aknowledgements

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