Infrastructure Interdependency Simulation Using i2Sim in a Study Case

H. Juárez García
Universidad Autónoma Metropolitana, Unidad Azcapotzalco, México

J. R. Martí & K.D. Srivastava
University of British Columbia, Vancouver, Canada)

SUMMARY:
The Infrastructure Interdependency Simulator (i2Sim) allows multiple infrastructures to be represented as a system of systems and solve for their external interactions (interdependencies).

Damage to the infrastructures during disasters and greater demand for resources creates a situation where decisions need to be made as to the optimum allocation of the available resources. The simulator supports look-ahead and rewind functions to predict the evolution of the system dynamics in order to assess in real time the effect of suggested decisions before they are actually applied to the real system.

i2sim will be used to model an incident during a sport event in the downtown area of a populated city. A number of casualties result from damage at a sport venue and from an egress process. The results of the study show that depending on the number of victims and on the conditions of the traffic routes, the facilities at the nearby hospitals are not sufficient and extra measures need to be taken to prevent a large number of fatalities.

Keywords: Infrastructure, Interdependency, Simulation, Disasters

1. INTRODUCTION

The utility of a tool like i2Sim is to provide a meaningful simulation of a disaster response scenario at the system level, showing clearly the impacts of events as they unfold as well as decisions made at all levels of response and coordination. These events and decisions will often affect the operations of multiple critical infrastructures in ways that are difficult or impossible to foresee without the use of such a tool. Iterating a disaster scenario in i2Sim allows both planners and response coordinators to quickly and easily evaluate the ultimate impacts of a given response strategy and level of coordination in terms of the most crucial metrics: human cost and overall system resiliency.

The i2Sim simulator was developed by the CIS Group (Complex Interdependent Systems Group) of the University of British Columbia to model interdependencies among critical infrastructure (CI) systems (e.g., electricity, water, gas, etc.). This permits coordinated decision making for optimum deployment of resources and priorities in system restoration. In case of a problem in the power grid, for example, i2Sim can determine which other infrastructures supply points, e.g., the water pumping station, the hospital, etc. should be served and which ones can be left without service until the system is repaired. Similarly, when multiple points of service need to be repaired, which points should be repaired first? With i2Sim, priorities in service and restoration can be coordinated among infrastructure owners and emergency responders so as to minimize injuries and loss of lives during disaster events.

To demonstrate the usefulness of i2Sim for a closer coordination of CI service availability with emergency responder actions, it has been proposed that the tool be used to simulate a disaster scenario. For this purpose, the capabilities of i2Sim have been extended to incorporate the following models: a) traffic model; and b) crowd egress model.

Due to their different nature, different infrastructures may use very different descriptions to model their operation. i2Sim defines a common ontology to describe the same type of functions in different infrastructures, Martí et al, (2008) and Juárez García (2010):

a) Cells: represent functional units. Functional units are modelled in terms of a production model that relates the inputs needed for the unit to produce its outputs. To describe the operability of the cells, i2Sim uses tables ("Human Readable Table", HRT) which indicate the available output in terms of the available input and the physical damage of the cell.
b) Channels: represent the means by which tokens are transported from a source cell to a consumption cell. Channels are characterized by a loss coefficient and by a time delay. The loss coefficient accounts for leakage, while the time delay accounts for the transportation time. In a similar way to the cell descriptions, channels are represented by HRT description tables but with the added parameter of a time delay.
c) Tokens: Quantities that are the inputs and the outputs of the cells.
d) Controls: Interface the physical layer with the decisions making layer.

2. I2SIM CAPABILITIES

The updated i2Sim model has the capability to simulate the following emergency response situations:

1) Damage to stadia and crowd egress
2) Traffic and street crowds
3) Damage to physical infrastructure
4) Damage to human infrastructure

2.1 Damage to Stadia and Crowd Egress

Events can combine: a) Damage and injuries caused by the disaster directly, and b) Injuries caused by egress of the crowd. After the victims have been taken out of the stadium, they are triaged and conducted to the care facilities.

i2Sim's egress model considers both the victims due to the physical event plus the victims due to the crowd egress process. For an earthquake or other physical damage events, there are assessment techniques to estimate the number of victims due to structural damage. For the crowd egress, i2Sim's new crowd egress model estimates casualties based on crowd density, guidance, rapid response, layout, and demographics. i2Sim's model for this situation is based on the concept of a primary factor: crowd density, adjusted by modifiers: guidance, rapid response, layout, demographics, and possibly others. Relationships between victims and density have been proposed in a number of references. i2Sim's concept of modifiers permits to incorporate the experience of the responders in this type of situations.

2.2 Traffic and Street Crowds

i2Sim can model these events based on the concept of density, similar to the stadia crowd egress model, adapted to motorized vehicles as well as to pedestrian crowds. In the model, the vehicle's speed is associated to the number of vehicles occupying a certain road (bridges or streets) segment (density) as a primary factor and length (distance), adjusted by modifiers: guidance, rapid response, weather conditions, road closures and road damage. An example of guidance is traffic lights not working due to power failure. Another example of guidance is the number of traffic officers redirecting traffic due to closures. An example of rapid response is the time required to clear an accident situation. In the model, vehicles density is readjusted after road closures or openings. Pedestrian crowds behave in a way similar to stadia egress crowds and are affected by density and corresponding modifying factors.

2.3 Damage to Physical Infrastructure

Evaluating the interdependencies among critical infrastructures (e.g., electricity, water, gas, health, etc.), and the importance of coordinating the delivery of limited resources and prioritizing the restoration of services is a main capability of i2Sim. Events causing physical damage to the operating infrastructure will have cascading effects in the overall system response. Damage to physical infrastructure can have effects lasting from hours to days. These kinds of events go beyond incident response and require an optimum ranking of essential services. Incidents lasting days instead of hours may exhaust the reserve capacity of major entities, for example the electricity reserve of Hospital 1 (H1) (48 hours) and Hospital 2 (H2) (72 hours). A larger magnitude earthquake would fall into this situation.

2.4 Damage to Human Infrastructure

Damage to Human Infrastructure corresponds to the non-availability of humans to perform essential infrastructure functions. These include first responders, disaster managers, decision makers, and policy makers on the system response side as well as on the critical infrastructure side (e.g., operators of power system control centres, crews to perform repair jobs, doctors and staff in hospitals, etc.).
Some events related to this type include:

a) Pandemics, e.g., H1N1
b) Maliciously induced events (e.g., water/food contamination)
c) Targeted personal attacks on key personnel

In i2Sim's current version, the effect of damage to human infrastructure can be modelled as reduced/slow operability of cells and channels. In some cases the degradation in operability can result in the "closing down" of the function, e.g., of a hospital, and in this case, it has the same effect as a building being destroyed by an earthquake.

3. SAMPLE COMPLEX SCENARIO: TRANSPORTATION & TREATMENT OF STADIUM VICTIMS DURING A MAJOR SPORT EVENT

The following sample scenario combines two main aspects of disaster response during complex situations: 1) Simultaneous major disaster incidents. A second major incident occurs within the time frame of the response to the first incident, thereby requiring a reallocation of infrastructure and response resources to optimize the overall system-wide objective of saving human lives; and 2) Illustrates the importance of coordinated versus distributed decision making in optimizing the delivery of insufficient resources and in setting resource restoration priorities by the utilities. It is important to notice that this General scenario was assumed as a base case scenario, but in this paper results from a particular scenario will be presented.

1. **Context:** the scenario takes place during a major sport event. It is assumed that this sport event will impose safety, transit and transportation constraints. For example Olympic Games or World Cup events.
2. **Participants:** Major and authorities of host City or Cities; Local and Global authorities; owners and managers of the sport venues; infrastructure managers; transportation stakeholders; emergency personnel (ambulances, Paramedics, Police and Firefighters); decision makers and other participants
3. **Environment:** it will be considered the following weather conditions: the average temperature range in February is 1^{o}C to 7^{o}C and there is a fair amount of precipitation (more than half the days will see some rain). Sunset: 5:07 pm to 5:51 pm.

The purpose of the scenario is to exert the relevant variables and their interrelationships. The scenario specifies the elements that must be kept in mind in the generic planning process or in the operational studies in relation with the deployment of local and global authorities. The scenario describes the global threat, the geographic area, the social objectives and the level of commitment.

3.1 Scenario Events

Major events: Double transformer failure due to an explosion in Electrical Substation M1. Substantial loss of service in the downtown core is reported. An uncontrolled multitude forms around Subway Station GSTS. At the time these incidents occur, a sport event is taking place at Venue B1. Within the time frame of the response to the first events, a stage with structural problems in B1 fails, causing a stage and related supporting infrastructure to collapse on top of spectators.

Critical Infrastructures affected: Substation (M1), Substation (C1), Substation (D1), Substation (S1), Water Station (WS), Hospitals (H1) and (H2), Venues (B1) and (G1), Roads Network, Subway Station (GSTS), and Ambulance Services (AS), **Figure 1** and **Figure 2** .

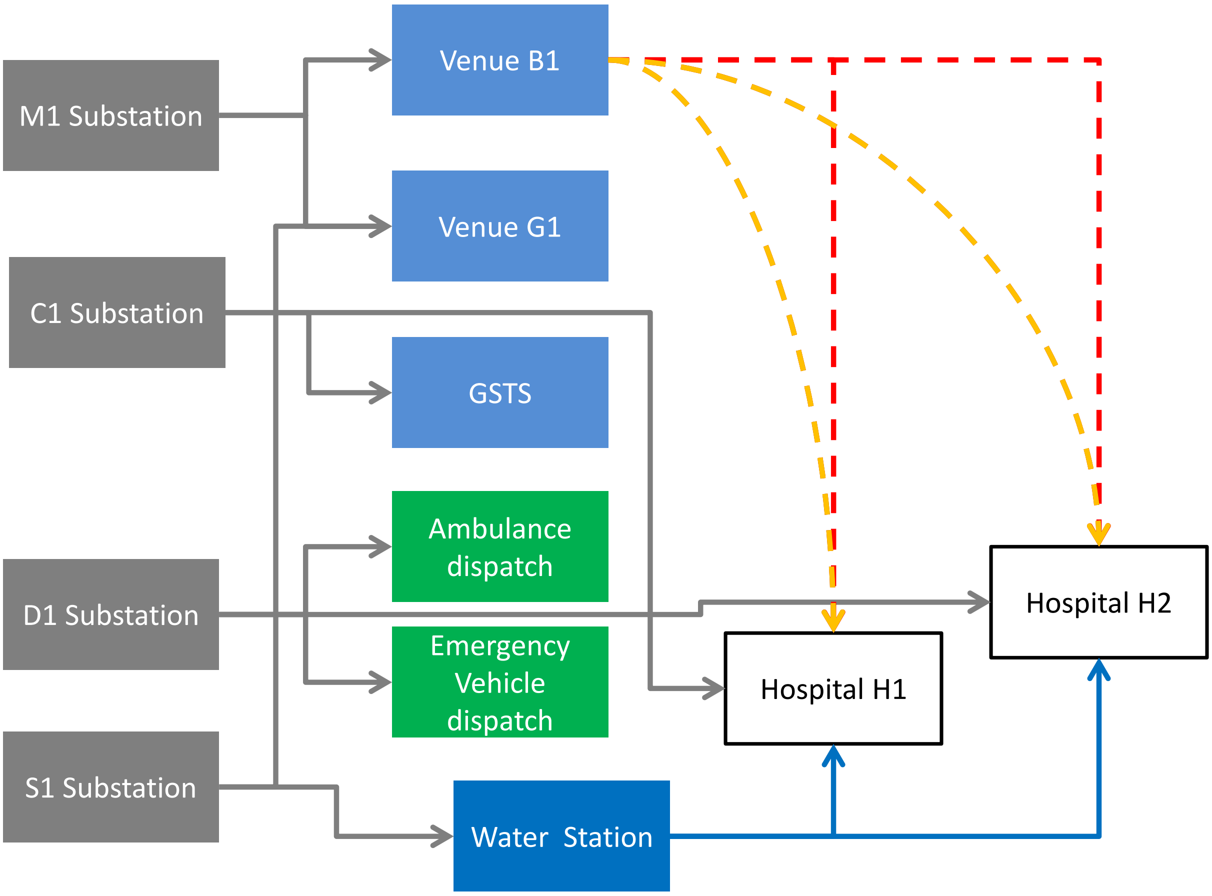

Figure 1. Concept model of the scenario

3.2 Evolution of events in time

In this simulation, the following six events were considered:

Event 1. [*Time : 00 minutes*] An explosion occurs in M1 Electrical Substation.
Event 2. [*Time : 00 minutes*] Traffic lights are out of service in major streets.

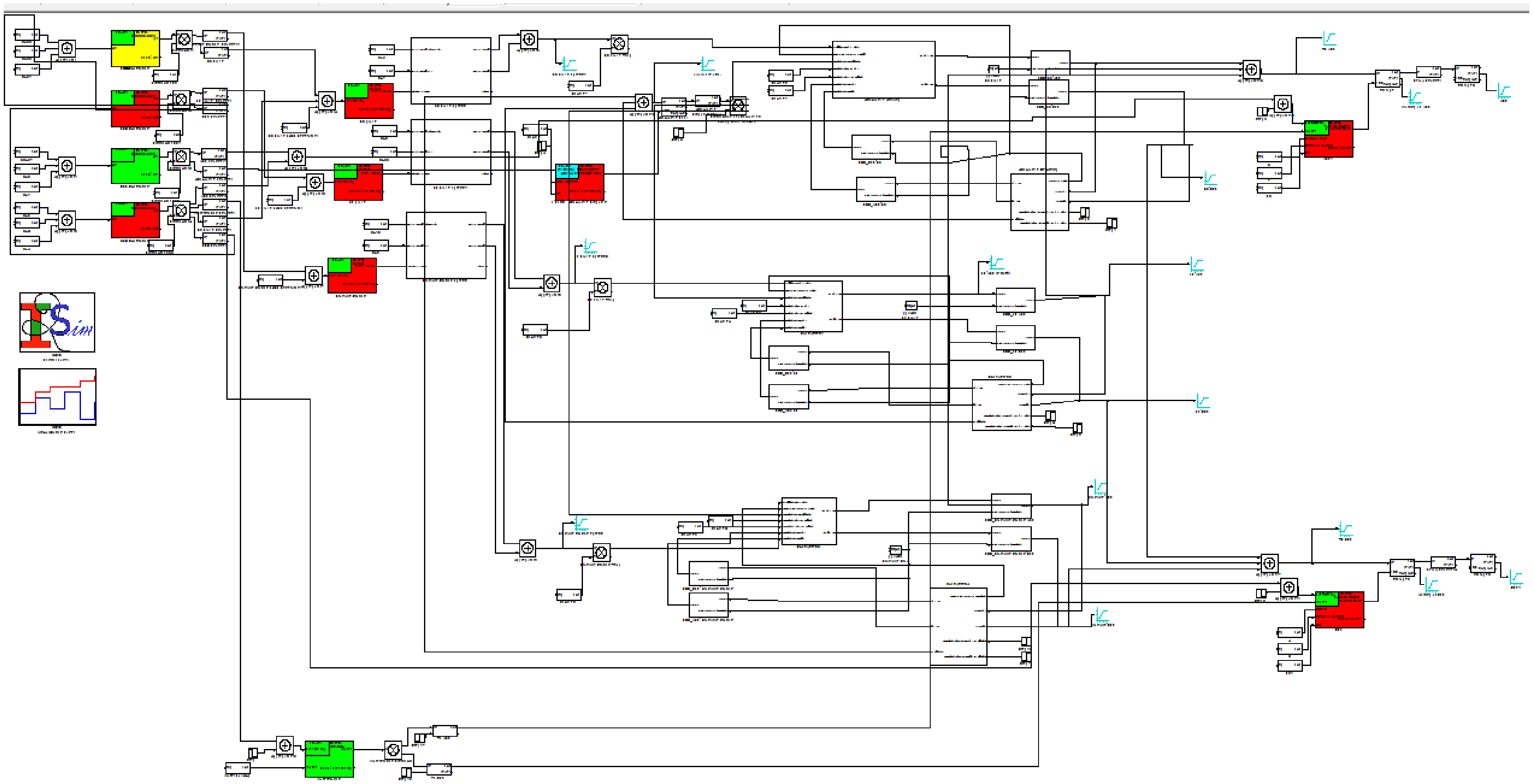

Figure 2. i2Sim General Model

Event 3. [*Time : 05 minutes*] A stage collapses on top of spectators near Venue B1
Event 4. [*Time : 06 minutes*] A multitude starts an uncontrolled egress from B1
Event 5. [*Time : 10 minutes*] Trapped people and casualties are reported in B1 after the collapse of the stage
Event 6. [*Time : 19 minutes*] Casualties are reported in B1 due to egress of spectators.

This is a general description of a complex scenario. This sample base case scenario can be modified to analyze other possible simultaneous events affecting two or more critical infrastructures. In the process of producing the model of i2Sim some aspects of this scenario have changed in order to produce significant results. In the following pages, a description of the models and the scenario will be described.

3.3 Transportation and Egress model in i2Sim

The model in i2Sim-ETran, infrastructure interdependency simulator, has egress and traffic model capabilities. In this scenario there is no physical damage to transportation infrastructures, but they have resource problems.

In this scenario, three venues and their egress models were modelled: B1, G1 and GSTS. The main objective of the egress model is to estimate the evacuation time and the number of casualties due to the egress process. Even though the egress models of all three venues have similar structures, their different physical attributes impose different metrics in their egress models.

The transportation time of casualties is critical in serving the objective of preserving human lives. In i2Sim, the traffic model determines the transportation time delay; this is taken as a function of speed and distance, and speed changes with various conditions: guidance, rapid response, weather conditions, road closures and road damage. i2Sim traffic model has the capability to simulate from normal road conditions to activated Disaster Response Route (DRR) network, with the possibility to include crowds in the streets.

In the model from the scenario, three traffic zones were considered in the model:

Zone 1: Venue perimeter, in this closed environment the traffic restrictions and the amount of pedestrians will create difficult road conditions.
Zone 2: Downtown core area, road restrictions and pedestrian streets will create different set of conditions.
Zone 3: Some of the roads will experience no-parking and non-stopping restrictions; for this model, some of the roads and transportation trajectories cross Zone 3 to access Hospital H2.

4. SIMULATION RESULTS

The model developed in i2Sim can reveal interdependencies and cascading effects during a disaster. The model can be used to perform sensitivity analysis and results to answer objective function questions.

For the example presented herein, three different assessment simulations will be discussed. The following objective function was defined for these simulations:

4.1 Objective: Evaluation of the time to assess and stabilize casualties at ERs in different Hospitals, and an estimation of the fatalities due to the delay in treatment of those casualties.

In order to address this objective, three conditions were run in the model:

1) Road conditions. Two hospitals were considered (H1 and H2); 30 casualties were defined (20

yellow-coded and 10 red-coded casualties) that were divided equally in both hospitals. The following road conditions were modeled with the transportation model developed in i2Sim:

- Normal road conditions
- Normal road conditions and no pedestrians. Emergency responders manage to contain pedestrians from accessing the emergency routes
- DRRs are immediately activated, this means no pedestrians and no traffic at all

2) Number of casualties. Two hospitals were considered (H1 and H2); casualties were divided equally in both hospitals. It was assumed the restricted transportation in point 1
   - 30 casualties
   - 50 casualties
   - 100 casualties
3) Large number of casualties was assumed in order to exhaust the Health Services of the City considered. Seven hospitals were modelled. It was assumed the restricted transportation conditions and immediate activation of DRRs.
   - 280 casualties
   - 860 casualties
   - 2,500 casualties

4.2 Results from road conditions

4.2.1 Time frame for the simulations

The following time criterion (timeframes) for transportation of casualties was assumed:

- Transportation of casualties (type 1 casualties) due to a collapsed stage at B1, **¡Error! No se encuentra el origen de la referencia.**:

t 1. Initial assessment. Once the structure has collapsed, trapped people will be requiring help and security personnel or spectators will assess the trapped and security conditions, and the extension of the damage due to the wreckage. **Figure 3** shows this time as 2 minutes; it was assumed that safety personnel at B1 will have enough knowledge as to quickly assess the situation and start helping and clearing the collapsed scene.

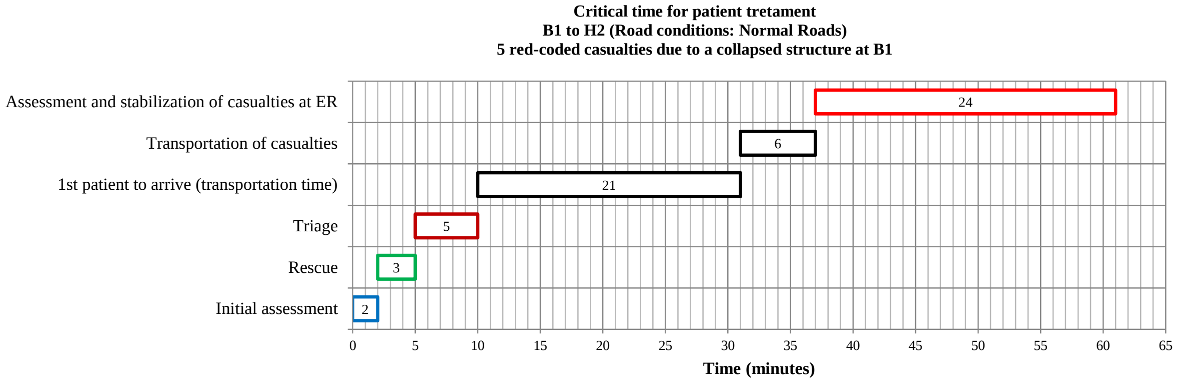

Figure 3. Critical time for patient treatment, collapsed structure at B1

t 2. Rescue of trapped people including triage time of the rescue process. Security personnel, first responders or spectators will try to pull out trapped people from the collapsed structure, in this process it will be decided the severity of injuries (triage). **¡Error! No se encuentra el origen de la referencia.** shows this time in two categories: rescue (3 minutes) and triage (5 minutes); it is assumed that there are paramedics inside B1, and that these first responders will attend the scene and they will quickly start the triage process.

t 3. Transportation of casualties (type 1) will commence at this moment in time. It is worth noting that transportation of casualties will be assumed with 2 ambulances at a time (first responders can handle two casualties and two ambulances every minute), if there are 5 red-coded casualties they will be pulled out, triage, handled, and transported to the ER systems at the hospitals. The transportation time, it is the time that it takes for an ambulance to arrive from Venue B1 to Hospital H2. **¡Error! No se encuentra el origen de la referencia.** shows transportation time as 21 minutes; but there is also an additional time for transportation of casualties (6 minutes). This is assumed to account for the time that ambulances take to line up, to prepare the casualty inside the ambulance, and the handling off the casualty once they have arrived to ER.

t 4. Assessment and stabilization of casualties at ER. Once the casualties have arrived to ER, it is assumed that 5 casualties will be handled in 30+ minutes, as H2 was supposed to have a 10 patients/hour rate. It was assumed that the human and physical resources to maintain the ER's rate will be focused on assessing and stabilizing the 5 red-coded casualties. Those 30+ minutes to stabilize the patients were assumed to account for aggressive ER treatment such as CPR or other medical procedures necessary for the casualties to undergo comprehensive treatment, such as trauma surgery, in which case the casualties are transferred to other hospital locations such as traumas, intensive care, OR units, etc. **¡Error! No se encuentra el origen de la referencia.** shows that red-coded casualties will be assessed and stabilize in 61 minutes since the events started unfolding. The transportation time shall be the addition of the time of initial assessment, rescue, triage, transportation time and transportation of casualties. The first patient will arrive after 31 minutes, and all red-coded patients will arrive after 37 minutes.

Two important issues should be mentioned: triage of mass casualty disasters differs in important ways from traditional triage processes: victims can be distributed in a wide area (this is true for earthquakes); medical resources are limited; the length of time before a patient can receive standard care is unpredictable; and early evacuation might not be possible, Schultz et al, 1996. CPR is not performed, unless sufficient resources are available without jeopardizing the lives of other victims. Dynamic triage techniques have developed to overcome these situations in mass casualty disasters, Benson et al, 1997.

In terms of triage for medical casualties, first responders and EMS staff are generally trained in a triage system known as START (simple triage and rapid treatment). Practitioners are trained to classify disaster survivors into four categories based on a colour-code scheme: Green (minor); Yellow (delayed); Red (critical); Black (diseased/expectant). The triage process assumed in this simulation takes into consideration the fact that a dynamic triage is in place at a time in B1. Hospital triages may use the same color-coded system. In the triage process it is assumed that black-coded are separated from the rest of the casualties; green-coded are released at the scene (walking wounded); yellow-coded and red-coded are transported to ERs. The transportation priority is red-coded casualties, those casualties will be transported first and then yellow-coded ones.

4.2.2 Egress and Transportation assumptions

The numbers were estimated by taking measurements at the venues and timing the evacuation of spectators after a game. The numbers represent the evacuation of the venues during normal conditions; the time was adjusted for an emergency evacuation case. For i2Sim Egress model the following assumptions were made:

- The triage process takes about 5 minutes for yellow and red-coded victims. The assumption is that for mass casualties "…*triage may involve providing some basic life saving measures, but it is not meant to be the time at which aggressive or definitive care is provided. It should be remembered that triage in a disaster situation is different from triage in a hospital setting in that the time to definitive care is unknown in a disaster situation*…", Delaney and Drummond, 2002.
- The number of casualties from the egress process is calculated based on the density of the spectators at the waiting area near the exits. It is assumed that when the density reaches 4 people/m^2, a percentage of evacuees would get injured (the majority will be green-coded casualties or minor injuries).

- Even though the model considers five modifying factors: Demographics, Guidance, Rapid Response, Layout and Electricity to estimate the number of casualties and the egress time. The lack of electricity is the only one that has a repercussion in the outcomes of this scenario. The external source of electricity is disconnected (M1 Substation is down) and only the emergency lights are on during the evacuation process. In this case, it is assumed that the lack of electricity increases the delay time and hence the number of casualties.

Assumptions for traffic model (speed considered for emergency vehicles):

1. Zone 1: Considered as the related parking areas and access streets of B1 and G1 Venues, a constant time delay is considered.
2. Zone 2: Downtown core area with pedestrians leaving B1. Maximum speed considered: 30 km/hr.
3. Zone 3: Area out of the downtown core, with normal traffic conditions. Maximum speed is 60 km/hr.
4. If vehicles travel in regular road network they will travel through all the three zones and will experience different speeds due to different road conditions. When DRR is activated the designated emergency vehicles can go through DRRs, traveling through different zones and without time delays. The maximum speed considered is 90 km/hr.

4.3 Results

A number of casualties were estimated, treatment time for casualties and possible fatalities due to delay in treatment: direct casualties related to damage and a stage collapsing on top of spectators inside B1; and indirect casualties related to crowd egress going out of control in B1.

Different number of victims was assumed in the simulations, **Table 1** shows important values from the simulations: the total treatment time and the fatalities due to delay in treatment

Constants: 30 ambulances, 1 casualty carried per ambulance

Response 1 – two hospitals (H1 and H2), and normal road conditions as explained before
Response 2 – H1 and H2, and immediate activation of Disaster Response Routes (DRRs)
Response 3 – H1 and H2, and Normal Roads and no pedestrians allowed in the routes
Response 4 – seven hospitals (including H1 and H2 and 5 located in the City), and immediate activation of DRRs; 30 ambulances, 2 casualties carried per ambulance

Table 1. Results: total treatment time and fatalities due to delay in treatment

No of Victims	Response 1	Response 2	Response 3	Response 4
30	121 minutes 2 deaths	110 minutes 2 deaths	116 minutes 2 deaths	
50		2 hr 49 m 6 deaths		
100		5 hr 19 m 25 deaths		
283				5 to 6 hours 135 deaths
864				15 to 18 hours 560 deaths
2,591				42 to 48 hours 1,700 deaths

5. CONCLUSIONS

A number of “reasonable” assumptions were made related to the evolution of the scenarios.

Triage of mass casualties during disasters differs in important ways from traditional triage processes.

The triage process assumed in this simulation takes into consideration the fact that a dynamic triage is in place at a time in B1. The transportation priority is red-coded casualties, those casualties will be transported first and then yellow-coded ones.

Three road conditions were investigated and timeframes for casualty treatment were also defined.

These road conditions were set up in order to verify their impact in the delay of time for treatment.

“Normal roads and no pedestrians” refers to roads during the duration of the sport event. This is a condition that might be enforced during any major sport event, like the Olympics or World Cups, since there will be dedicated pedestrian streets in those type of events.

The process for transporting victims from the place where the disaster occurs to the ER in a nearby hospital, involves several activities.

DRR conditions have a significant impact in the transportation time.

For a moderate to low number of casualties, 15 Red-coded casualties can be assessed and stabilized within 2 hours; this is a limiting factor of ERs. Red-coded casualties can be sent to nearby hospitals, while some of the yellow-coded victims could be re-directed to further away hospitals to increase their overall chances for survival.

The situation for a large number of casualties (200 or more) shows that extraordinary measures need to be taken in order to reduce the transportation time, and the assessment and stabilization of victims. Field hospitals and other means of transportation might need to be implemented. It is likely that 200 victims could be handled within the region, but more than a 1,000 victims might compromise the response and the chance of survival unless emergency decisions are made to handle mass casualties.

AKCNOWLEDGEMENT
We would like to thank Paul Cottle, Shaharzad Rostamirad, Ruvini Kankanamalage and Elsa Pelcastre Pérez for their contribution on this paper.

REFERENCES

Martí, J.R., Hollman, J.A., Ventura, C.E., Jatskevich, J. (2008). *Dynamic recovery of critical infrastructures: real-time temporal coordination*. International Journal of Critical Infrastructures (IJCI), Vol. 4, Nos. 1/2, pp. 17-31.
http://www.ece.ubc.ca/~jiirp/JIIRP_Open_Publications/jiirp_i2c_043.pdf

Martí, J.R., Ventura, C.E., Hollman, J.A., Srivastava, K.D. and Juárez García, H. (2008 a). i2Sim Modelling and Simulation Framework for Scenario Development, Training, and Real-Time Decision Support of Multiple Interdependent Critical Infrastructures during Large Emergencies, NATO, RTA/MSG Conference on “How is Modelling and Simulation Meeting the Defence Challenges Out to 2015?” – Vancouver, Canada.

UBC-JIIRP Final report (2009). CIS Research Group at the University of British Columbia.

Schultz C.H., Koenig, K.L. and Noji E.K. (1996). “A Medical disaster response to reduce immediate mortality after an earthquake”. Massachussets Medical Society; The New England Journal of Medicine, Vol 334, No. 7: pp 438-444

Benson M., Koenig K.L. and Schultz C.H. (1997). “Disaster triage: START, then SAVE: a new method of dynamic triage for victims of a catastrophic earthquake”. Prehospital Disaster Med; Vol 11 No 2: pp 117-24.

Delaney J.S., Drummond R., Ducharme J. and Marx R.G. (2002). “Mass casualties and triage at a sporting event”. British Journal of Sports Medicine; Vol 36: pp85–88

Santy, P. Marquis Moulinier, (1918). “Da Shock Tramatique dans les blessures de Guerre, Analysis d'observations”. Bull. Med. Soc. Chir., 1918, 44: 205.
http://www.trauma.org/archive/history/resuscitation.html