Interdependent Critical Infrastructure (CI) Sector Analysis for the Emergency Management Mission

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Abstract

- The Emergency Management (EM) mission requires first responders to attend and assist the public in times of need. There are different missions, users, and CI sectors that are required for these missions to be successfully executed.
- Several common CI sectors are used for these missions and have some interdependency with other sectors.
- We provide a methodology to describe the EM mission space through a series of functional architecture artifacts, define their dependencies on the CI sectors, and model the CI-CI sector interdependencies. If disturbances occur to one or more CI sectors, other CI sector performance may be affected due to the interconnected relations, and may consequently affect the EM mission performance.
- Through this methodology, we offer a means to quantify the interdependencies and provide insight to decision makers on the importance of where the CI sectors contribute to the EM mission execution.
- This insight may address future resiliency planning, recovery, or restoration priorities to optimize expected EM mission performance. A series of interconnected executable models are combined with a notional example to illustrate the impact of such interdependencies.

Methodology Review

- **Define the EM mission space and their EM mission functions**
- **Transform the functional flow into an executable model**
- **Show the CI sector contributions to the EM mission functions**
- **Exercise the EM mission functional model and observe the results**

EM Mission Space and Functions

- **Research the EM responder functions and decompose them**

EM Responder Functions

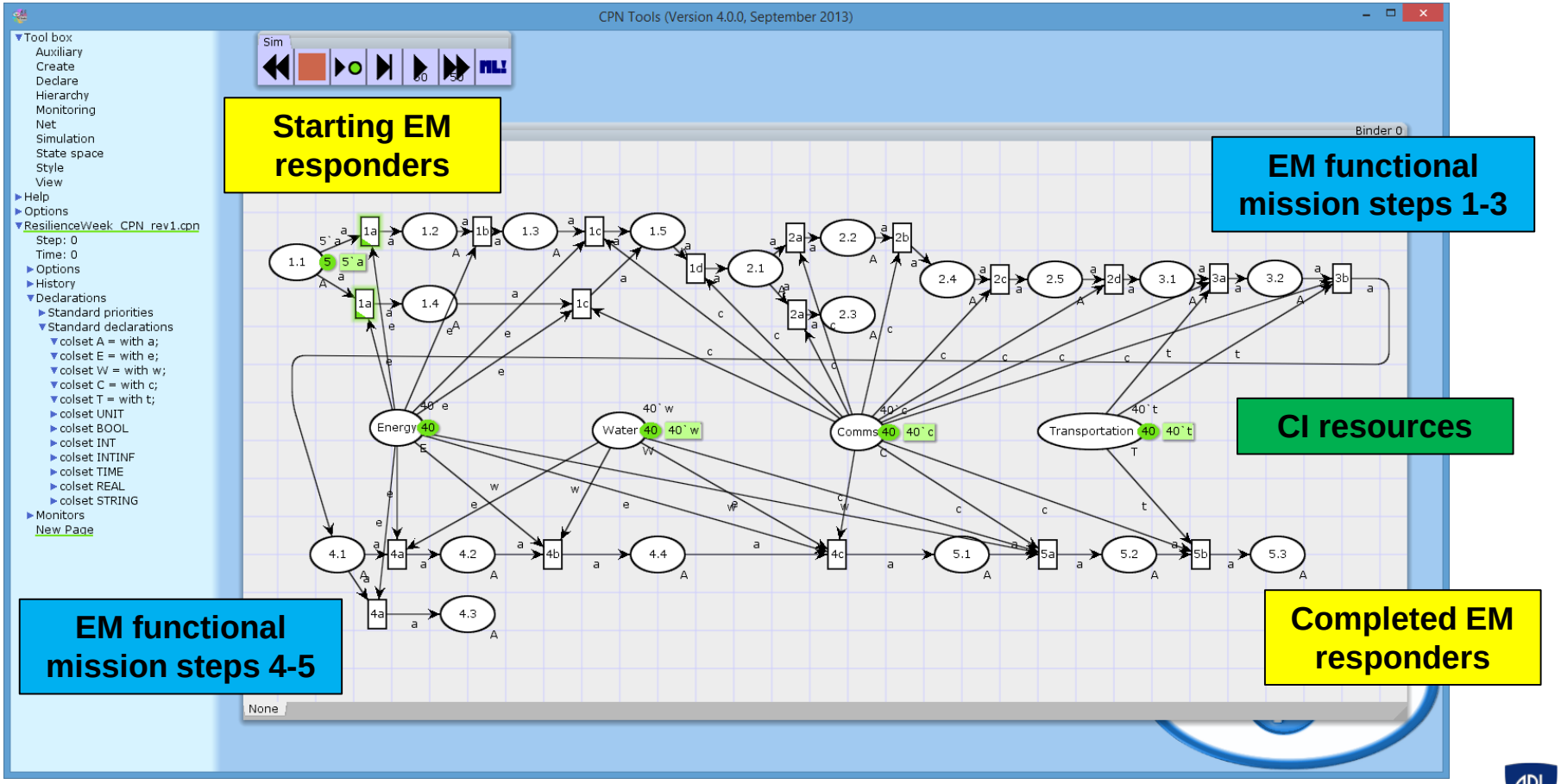
1. Monitor Situation → 2. Select Response Units → 3. Transit to Incident → 4. Respond to Incident → 5. Redeploy to Base

- **Allocate the specific CI sectors to each of the subfunctions**

Function	Description	Energy	Water	Comms	Transportation
1.1	Monitor sensors				
1.2	Passively sense environment	x			
1.3	Determine if action meets threshold for action	x			
1.4	Actively initiate alarm	x			
1.5	Send incident report	x		x	
2.1	Query available units in vicinity			x	
2.2	Receive available units reply			x	
2.3	Receive unavailable units reply			x	
2.4	Select closest unit to dispatch			x	
2.5	Receive acknowledgement			x	
3.1	Transit to site and receive enroute updates			x	
3.2	Arrive on site			x	x
4.1	Setup equipment and connect to CI resources			x	x
4.2	Use successful CI resources	x	x		
4.3	Do not use unsuccessful CI resources	x			
4.4	Respond to incident	x	x		
4.5	Resolve incident and report completion	x	x		
5.1	Pack up equipment and disconnect from CI resources	x	x	x	
5.2	Transit to base and report on status	x	x	x	
5.3	Return to base			x	x

Development of Executable Model

- The mission flow is then converted into an executable model
- In this case, we use the Colored Petri Net toolset (http://cpntools.org)

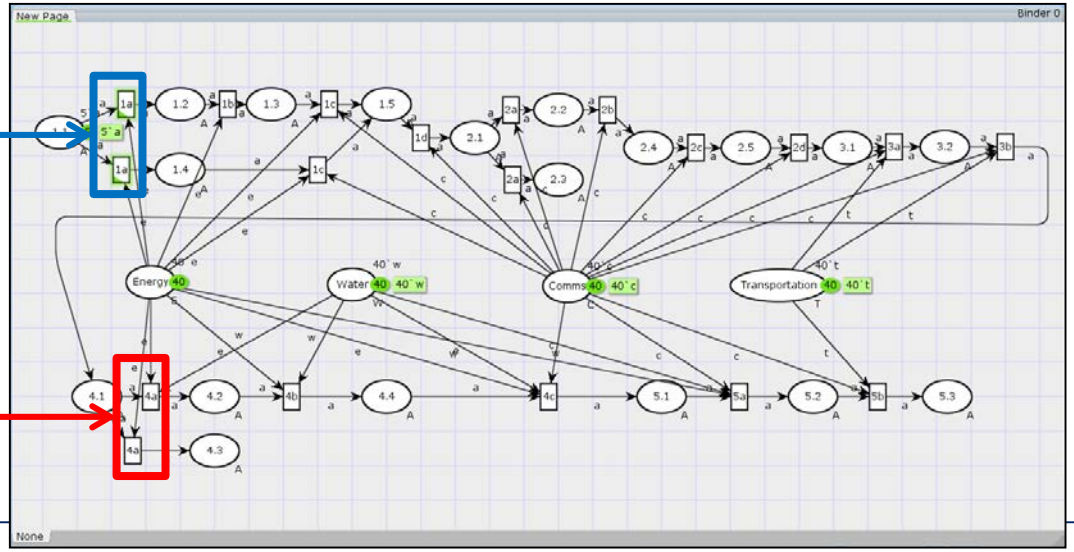


Run Execution

- The CPN tool is run to evaluate the level of EM mission accomplishment
- For a CPN, there are several areas where a stochastic element is introduced to select one of the two choices, in this case
  - Whether a EM responder is available or not (yes / no)
  - Whether a CI resource is available or not on scene (yes / no)
- The output is how many of the EM responders are able to complete their mission by successfully executing all of their functions

EM responder availability

CI resource availability



Results Interpretation

- We may execute the model numerous times to evaluate how well the functions are executed, how many unavailable responders and CI resources will affect the EM mission
- As more missions are successfully completed, the energy and communications sectors are used more in the latter phases of the mission
- Transportation is used when responders are more available to transit to the scene
- Water is used when the CI resources are available at the incident

Unavailable responders	Unavailable resources	Successful EM mission	Remaining energy	Remaining water	Remaining comms	Remaining transportation
4	1	0	22	40	20	38
3	2	0	27	40	15	36
3	2	0	25	40	15	36
3	2	0	26	40	15	36
3	1	1	23	36	12	35
3	1	1	22	36	12	35
2	1	2	18	32	4	32
2	1	2	17	32	4	32
2	1	2	18	32	4	32
1	1	1	17	30	0	31

Next Steps

- **We have developed a methodology to convert the functional architecture into an executable model**
- **By exercising the model with various inputs, we may show where the functional steps succeed and fail dependent on the amount of resources allocated to each of the functions**
- **By executing a fairly simplistic run matrix, we may also draw some conclusions on the importance of selected CI sectors to the functions**
- **Further research may incorporate a series of more complex and interdependent mission sets**
- **Additional types of executable models may be used to represent the mission functionality**

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Description of CPN Model

- **A CPN is a form of a Discrete Event Simulation**
  - **The two main components are places and transitions**
  - **Arcs connect the places and transitions**
  - **Colors are means to distinguish the different places and exchange tokens between the places via the transitions**
  - **Compound logics can then be described using multiple conditions in order to "fire" the transition**
- **We may convert our functional architecture:**
  - **Representing functions by the CPN transitions**
  - **Representing resources (CI sectors) by the CPN places**
  - **Allocating resources to the various places can then describe the amount of contribution that each function can accept**
- **By organizing the transitions as the sequential functions, we may then evaluate which functions are satisfied with the given resources**

References

- [1] DHS critical infrastructure sectors, http://www.dhs.gov/critical-infrastructure-sectors, 2014.
- [2] Presidential Policy Directive 21, Critical Infrastructure Security and Resilience, https://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil, 2013.
- [3] Balducelli, Claudio, et al. "Safeguarding information intensive critical infrastructures against novel types of emerging failures." Reliability Engineering & System Safety 92.9 (2007): 1218-1229.
- [4] Wang, Jiacun, William Tepfenhart, and Daniela Rosca. "Emergency response workflow resource requirements modeling and analysis." IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 39.3 (2009): 270-283.
- [5] Fiedrich, Frank, Fritz Gehbauer, and U. Rickers. "Optimized resource allocation for emergency response after earthquake disasters." Safety science 35.1 (2000): 41-57.
- [6] Dunn, Sarah, et al. "Network theory for infrastructure systems modelling." Proceedings of the ICE-Engineering Sustainability 166.5 (2013): 281-292.
- [7] Chen, Rui, et al. "Coordination in emergency response management." Communications of the ACM 51.5 (2008): 66-73.

Needs / Motivation

- **The Emergency Management (EM) responders require the use of selected Critical Infrastructure (CI) sectors in order to accomplish their missions.**
- **However, when some of these CI sectors are degraded, there is no quantified methodology to show how degraded the EM missions will become.**
- **By developing a methodology to describe the functionality and then convert to an executable model, we may evaluate how well the performance may result in the modification of the CI sector resources.**

Literature Review

- The motivation to study the CI sector operations and interdependencies originates from the Department of Homeland Security (DHS) critical infrastructure sector descriptions [1], and attention to maintaining these CI operations as stated by Presidential Policy Directive 21, Critical Infrastructure Security and Resilience [2].
- CI sectors are becoming increasingly automated and interlinked [3], which can increase the potential risk of degradation and disruption (via intentional attack, natural disaster, or accident).
- Wang et al. [4] use workflows to describe the sequential and parallel steps to graphically display the relevant actions and decision flows that EM responders and managers would encounter, which we may extend this concept to evaluating how well and where does the EM mission flow get stressed.
- Analysis techniques have focused more on the network structure that is disturbed (Fiedrich et al. [5]) and Dunn et al. [6]. We can leverage and extend the network structure towards a workflow-type analysis.
- Chen et al. [7] studies resource allocation decisions, particularly in various phases of the incident, using the 2001 CSX train derailment in Baltimore MD as a case study for their methodology. We can use our approach to look at the different phases of operations and evaluate how well these are conducted.

Emergency Management Mission Functions

- **EM mission functions:**
  - **1.1 Monitor sensors**
  - **1.2 Passively sense environment**
  - **1.3 Determine if action meets threshold for action**
  - **1.4 Actively initiate alarm**
  - **1.5 Send incident report**
  - **2.1 Query available units in vicinity**
  - **2.2 Receive available units reply**
  - **2.3 Receive unavailable units reply**
  - **2.4 Select closest unit to dispatch**
  - **2.5 Receive acknowledgement**
  - **3.1 Transit to site and receive enroute updates**
  - **3.2 Arrive on site**
  - **4.1 Setup equipment and connect to CI resources**
  - **4.2 Use successful CI resources**
  - **4.3 Do not use unsuccessful CI resources**
  - **4.4 Respond to incident**
  - **4.5 Resolve incident and report completion**
  - **5.1 Pack up equipment and disconnect from CI resources**
  - **5.2 Transit to base and report on status**
  - **5.3 Return to base**

- **Interfaces between functions (transitions):**
  - **1a Determine active or passive alarm initiation**
  - **1b Determine alarm threshold**
  - **1c Send alarm**
  - **1d Send request for responders**
  - **2a Determine available / unavailability of responders**
  - **2b Signal sent from available responder**
  - **2c Send assignment to responder**
  - **2d Assignment confirmation message**
  - **3a Status message and use of transportation**
  - **3b Reporting on site message**
  - **4a Determine available / unavailability of CI resources**
  - **4b Use of resources and status of incident**
  - **4c Incident resolution message**
  - **5a Departure of site message**
  - **5b Status message and use of transportation**