CRITICAL INFRASTRUCTURE PROTECTION TOOLS: CLASSIFICATION AND COMPARISON

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ABSTRACT

Recent research has shown that Critical Infrastructures are highly interconnected, whether they are manifested as processes, systems, facilities, assets, or services. The modeling and analysis of these interdependencies is a research field with an increasing interest. Dependency and risk analysis of these interconnections can be a computationally intensive problem but can also yield useful results that aid risk assessments and offer risk mitigation alternatives. This paper identifies and classifies most existing tools, frameworks, and methodologies that can serve as a common baseline for threat identification and risk assessment. Then, it compares their attributes and technologies. Conceptual and qualitative studies about infrastructure interdependencies, as well as their modeling and simulation approaches, are also examined. The comparison of the tools is based on two different aspects, i.e., the purpose (i.e. functionality goal) that each tool serves, as well as its technical modeling approach. For tools that are not publicly available, the classification used information from published articles and reports.

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1. INTRODUCTION

Critical Infrastructures (CIs), as referred to by the United States (US) Dept. of Homeland Security, are "*the assets, systems, and networks, whether physical or virtual, so vital that their incapacitation or destruction would have a debilitating effect on security, national economy security, national public health or safety, or any combination thereof*" [1]. CIs protection methodologies, models and simulations may be used to understand infrastructure systems, their interdependencies, their vulnerabilities, and the impact of potential failures and their propagation across interdependent infrastructure systems, based upon risk assessment reports for all CIs involved. These methodologies may also be used to support training exercises, performance measurement, conceptual design, impact evaluation, response planning, vulnerability analysis and economic impact.

The goal of this paper is to capture the current information and compare existing Critical Infrastructure Protection (CIP) tools and methodologies that can serve as a common baseline mainly for CI risk analysis and assessment.

2. CLASSIFICATION AND COMPARISON OF CIP MODELING TOOLS

We have based the classification and comparison of CIP related tools and methodologies on two different aspects: (a) the *Purpose* (i.e. functionality) served by each tool [1,11], and (b) their *Technical Modeling Approach* [6]. The categories used for each classification are:

- for classification based on purpose: (i) *risk identification*, (ii) *risk assessment*, (iii) *risk prioritization*, (iv) *risk mitigation planning,* and (v) *effectiveness evaluation*.
- for classification based on technical approach: *(i) Empirical approaches, (ii) System dynamics based approaches, (iii) Agent based approaches, (iv) Network based approaches and (v) Other approaches.*

In this paper we identified and analyzed 68 CIP tools, most of which were developed in the United States [2] (a brief description of these tools is included in the appendix).

2.1 CLASSIFICATION OF CIP TOOLS BASED ON THEIR PURPOSE

According to the National Infrastructure Protection Plan (NIPP) [11], tools, frameworks, and methodologies are classified according to the purpose that they serve, i.e. the stage of the risk management framework that they aid with their output. A model of the serial process is shown in Figure 1 (based on the NIPP Risk Management Framework).

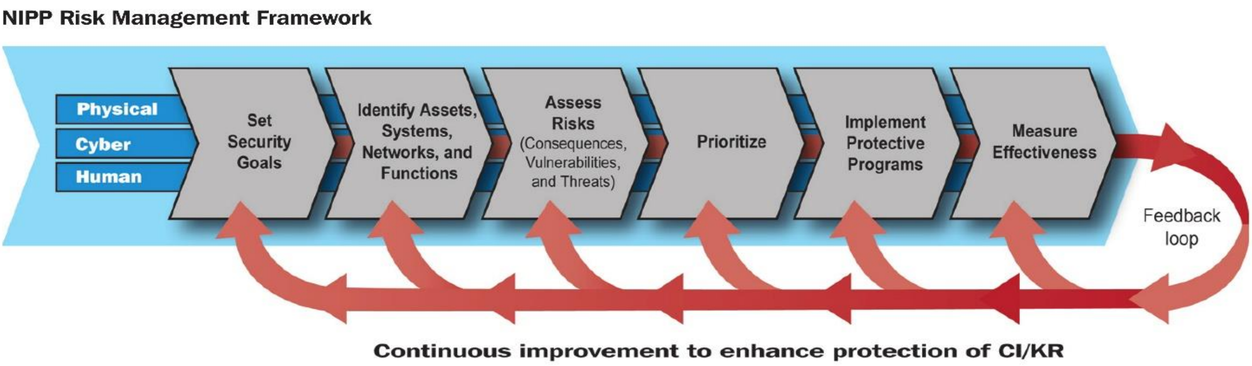

Figure 1. NIPP framework for Cis protection and risk management [11]

After setting the security goals, the following goals should be achieved, in serial order:

1. *Risk Identification* (RI): Identification of assets, potential vulnerabilities and events along with relationships.
2. *Risk Assessment* (RIA): Assessment of probabilities and consequences of risk events. May include cost, schedule, performance impacts and functionality impacts.
3. *Risk Prioritization Analysis* (RP): Aggregate and analyze risk assessment results, establish priorities that provide the greatest mitigation of risk. Criticality of risk is assessed with the use of decision-analytic rules, applied to rank risk events from most critical to the least.
4. *Risk Mitigation Planning and Implementation* (RMP): Selection of sector-appropriate protective actions or programs to reduce or manage the risk identified.
5. *Effectiveness Evaluation* (EE): The effectiveness of selected measures and strategies is evaluated. Existing and newly identified risk events are reassessed.

Figure 2 depicts the classification of the 68 tools according to the risk management purpose served. Tools that lie deeper than others in the same branch support additional risk analysis purposes, *i.e.* they support additional stages of the risk management framework.

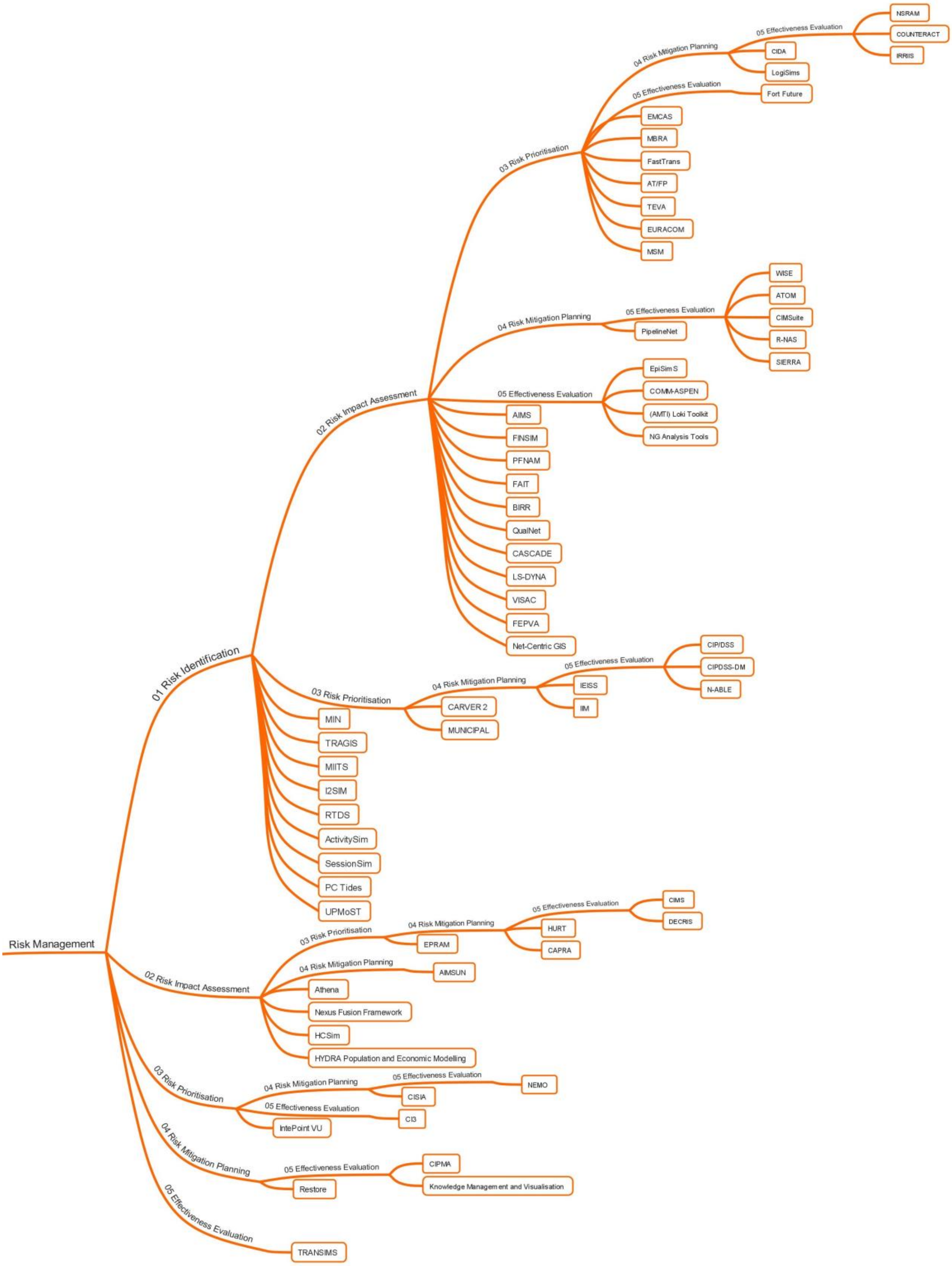

Figure 2. CIP tools classification according to risk management purpose

As shown in the classification tree, the majority of the tools start with the risk identification stage and then proceed to further analysis steps. Only few tools skip the first two stages, while even fewer ones (i.e., 3) support all the stages of the Risk Management Framework.

2.2 CLASSIFICATION BASED ON MODELING APPROACH

CI modeling approaches refer to the techniques used during the development of CIP tools. They are often chosen based on the intended purpose of every tool. All approaches serve risk assessment purposes, but there are some unique characteristics to every approach. Ouyang [6] categorized CIP tools and methodologies using five main types of modeling and simulation approaches:

- *Empirical approaches***:** The empirical approaches analyze CIs interdependencies according to historical events, disaster data and expert knowledge. They can identify failure patterns, quantify interdependency strength metrics to aid decision making, perform empirically-based risk analysis and provide alternatives to minimize risk in interdependent infrastructures.
- *System dynamics based approaches:* System dynamics-based approaches utilize a top-down method to manage and analyze complex adaptive systems involving interdependencies. Feedback, stock and flow are the basic concepts in this type of approaches. Feedback loops indicate connection and direction of effects between CI components.
- *Agent based approaches:* Agent based approaches are the most common tool-building techniques. Due to the inherent complexity of CIs and the related decision-making processes, CIs are usually regarded as *Complex Adaptive Systems* (CAS). To analyze CAS, agent-based approaches adopt a bottom-up method and assume that complex behavior or phenomena emerge from many individual and relatively simple interactions of autonomous agents. Most CI components can be viewed as agents. A model's agent interacts with others and its environment, based on a set of rules, which mimic the way a real counterpart would

react. Hence, agent-based approaches are widely used to model the CI interdependencies, and are mainly used by several national laboratories.

- *Network based approaches:* In network based approaches CIs are described as networks where nodes represent different CIs components and links mimic the physical and relational connections among them. Thus they can provide an intuitive CI representation along with descriptions of topologies and flow patterns. Performance response of CIs to hazards can also be analyzed by modeling the component failures from hazards at component level and then simulating cascading failures within and across CIs at system level.
- *Other approaches:* Other approaches exist that can model and analyze interdependent CIs, such as models of economic interdependencies, cellular automata, mathematical equation and others. Namely, we identified four major miscellaneous approaches: (i). Economic Theory-based, (ii). Cellular Automata-based, (iii). Mathematical Equation-based and (iv). Real-Time Simulation-based.

CI modeling seems to be associated with simulation techniques and mathematical models that are combined with the above mentioned computational techniques like continuous time-step simulation, discrete time-step simulation, Monte Carlo simulation, decision trees, Geographical Information Systems (GIS), risk management techniques, etc.

In the following classification tree, the Ouyang's approach classification model [6] is used in order to categorize the examined CIP software tools. Each tool has been assigned to one category, in an effort to map all detected CI analysis software. Many CIP methodologies are hybrid (i.e. belong to more than one approach). The same is true for some tools, i.e., they may belong to more than one category. Hybrid methodologies/tools have been categorized based on their dominating (i.e. most appropriate) category and further classified based on additional approaches used; the deeper a methodology/tool is positioned in the approach classification tree in Figure 3, the more complicated simulation technique is used.

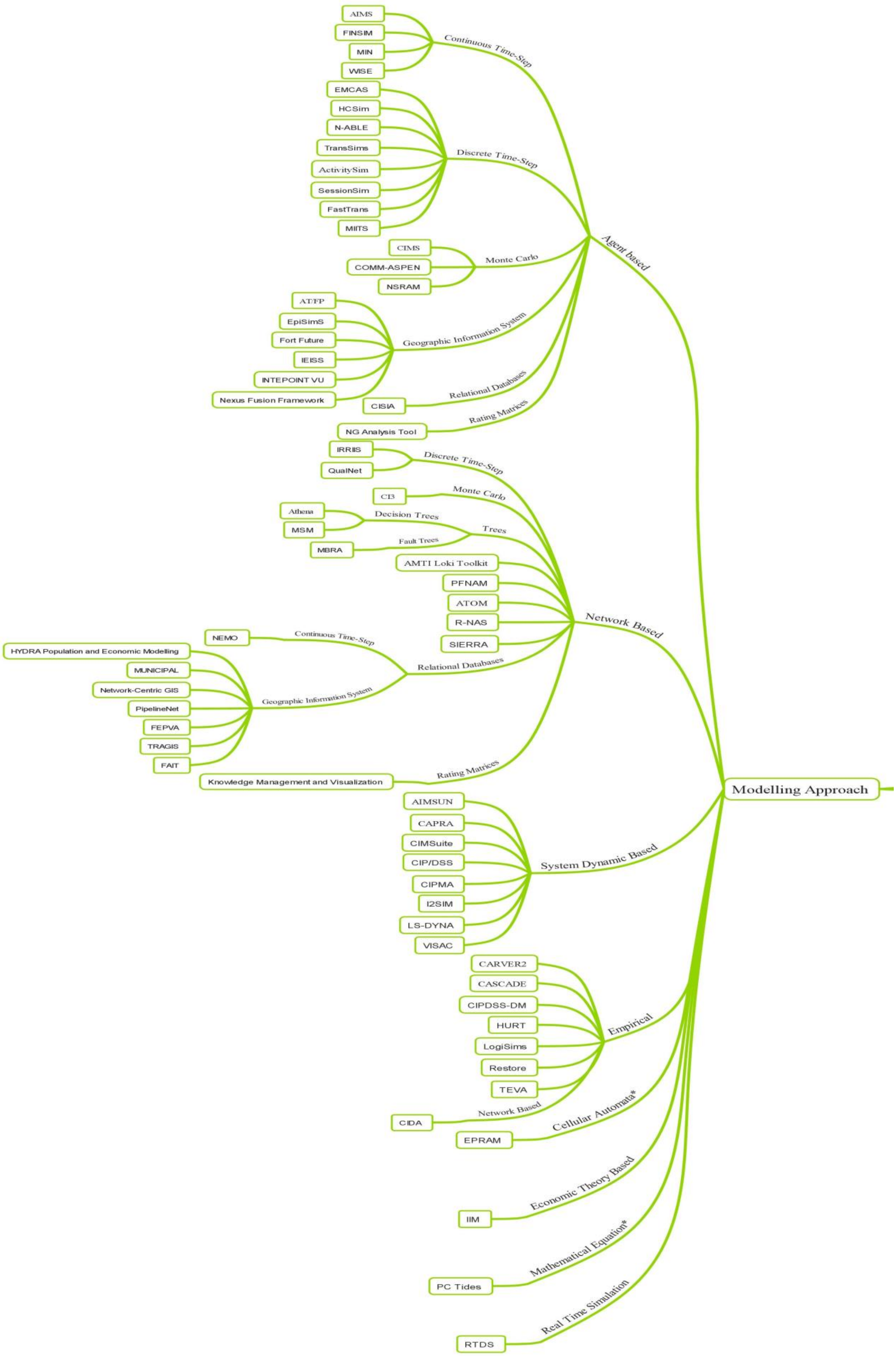

Figure 3. CIP tools classification according to modeling approach

The majority of tools are using Agent based or Network based approaches to perform the modeling and risk analysis report. Then, they are further categorized according to supplementary modeling techniques (Continuous/discrete time-step simulation, Decision trees, GIS, etc.).

2.3 CLASSIFICATION SUMMARY

The US Dept. of Homeland Security [3] has identified sixteen CI sectors (Table 1).

Critical Infrastructure Sector	Prefix	Critical Infrastructure Sector	Prefix
Chemical	CH	Financial Services	FS
Commercial Facilities	CF	Food & Agriculture	FA
Critical Manufacturing	CM	Government Facilities	GF
Dams	D	Healthcare & Public Health	HPH
Defense Industrial Base	DIB	Information Technology	IT
Emergency Services	ES	Nuclear Reactors, Materials & Waste	NRMW
Energy	E	Transportation Systems	TS

Table 1. Sector prefixes

We use the prefixes in Table 2, so as to depict sectors covered by each tool. Abbreviation prefixes for risk purpose and modeling techniques are presented in Figure 5, while Figure 4 presents the comparison aspects used for the classification of the CIP tools.

Figure 4. Comparison aspects for CIP tools classification

Purpose Functionality	Prefix
Risk Identification	RI
Risk Impact Assessment	RIA
Risk Prioritization	RP
Risk Mitigation Planning	RMP
Effectiveness Evaluation	EE

Modelling Technique	Prefix
Continuous Time-Step	CS
Decision Trees	DT
Discrete Time-Step	DS
Geographic Information System	GIS
Monte Carlo	MC

Figure 5. Classification abbreviation prefixes

In Table 2 we have summarized all the examined CIP tools and methodologies, based on their modeling approaches, risk purpose functionalities, and the CI sectors each tool can support.

Tool/Methodology	Modelling Approach	Purpose/ Functionality	CI Sector
ActivitySim	Agent Based, DS	RI	CF
AIMS	Agent Based, CS	RI, RIA	CF, C, E, IT, WWS
AIMSUN	System Dynamic Based	RIA, RMP	TS
AMTI Loki Toolkit	Network Based	RIA, EE	E, FS, TS
AT/FP	Agent Based, GIS	RI, RIA, RP	DIB, ES, HPH, TS
Athena	Network based, DT	RIA	CF, C, CM, DIB, E, FS, IT, NRMW, TS, WWS
ATOM	Network based	RI, RIA, RMP, EE	TS
BIRR	Methodology (no modeling)	RI, RIA	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CAPRA	System Dynamic Based	RIA, RP, RMP	FS, HPH, TS, WWS
CARVER2	Empirical	RI, RP	HPH
CASCADE	Empirical	RI, RIA	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CI3	Network Based, MC	RP, EE	C, CM, E, NRMW, WWS
CIMS	Agent Based, MC	RIA, RP, RMP,EE	CF, C, E, HPH, TS
CIDA	Empirical Based, Network Based	RP, RMP, EE	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CIMSuite	System Dynamic Based	RI, RIA, RMP, EE	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CIP/DSS	System Dynamic Based	RI, RP, RMP, EE	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CIPDSS-DM	Empirical	RI, RP, RMP, EE	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
CIPMA	System Dynamic Based	RMP, EE	C, E, FS, IT, TS
CISIA	Agent Based, Relational Databases	RP, RMP	C, CM, E, NRMW, WWS
COMM-ASPEN	Agent Based, MC	RI, RIA, EE	C, E, FS
COUNTERACT	Methodology (no modeling)	RI, RIA, RP, RMP, EE	E, HPH, TS
DECRIS	Methodology	RIA, RP, RMP,EE	C, E, IT, TS, WWS
EMCAS	Agent Based, DS	RI, RIA, RP	C, E, FS, WWS
EpiSimS	Agent Based, GIS	RI, RIA, EE	HPH
EPRAM	Cellular Automata	RIA, RP	E
EURACOM	Methodology (no modeling)	RI, RIA, RP	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
FAIT	Network Based, GIS, Relational Databases	RI, RIA	ES, E, FS, NRMW, TS
FastTrans	Agent Based, DS	RI, RIA, RP	TS
FEPVA	Network Based, GIS, Relational Databases	RI, RIA	E
FINSIM	Agent Based, CS	RI, RIA	C, E, FS
Fort Future	Agent Based, GIS	RI, RIA, RP, EE	CF, C, CM, DIB, E, FS, HPH, IT, NRMW, TS, WWS

HCSim	Agent Based, DS	RIA	D, HPH, NRMW
HURT	Empirical	RIA, RP, RMP	HPH
HYDRA Population & Economic Modeling	Network Based, GIS, Relational Databases	RIA	FS, HPH
I2SIM	System Dynamic Based	RI	CF, CM, HPH, T
IEISS	Agent Based, GIS	RI, RP, RMP	E, NRMW, WWS
IIM	Economic Theory Based	RI, RP, RMP	C, E, FS, IT, TS, WWS
INTEPOINT VU	Agent Based, GIS	RP	CF, C, E, TS
IRRIIS	Network Based, DS	RI, RIA, RP, RMP, EE	C, CF, CM, D, DIB, ES, E, FS, FA, GF, HPH, IT, NRMW, TS, WWS
Knowledge Manage-ment & Visualization	Network Based, Rating Matrices	RMP, EE	E, TS, WWS
LogiSims	Empirical	RI, RIA, RP, RMP	E, HPH
LS-DYNA	System Dynamic Based	RI, RIA	CM, D, TS
MBRA	Network based, FT	RI, RIA, RP	E, FS, TS
MIITS	Agent Based, DS	RI	C, IT
MIN	Agent Based, CS	RI	CF, TS
MSM	Network based, DT	RI, RIA, RP	E, HPH, WWS
MUNICIPAL	Network Based, GIS, Relational Databases	RI, RP	C, E, IT, TS
N-ABLE	Agent Based, DS	RI, RP, RMP, EE	E, FS, TS
NEMO	Network Based, GIS, Relational Databases	RP, RMP, EE	C, DIB, E, TS, WWS
Net-Centric GIS	Network Based, GIS, Relational Databases	RI, RIA	TS, WWS
NEXUS Fusion Framework	Agent Based, GIS	RIA	CF, C, DIB, E, TS
NG Analysis Tools	Agent Based, Relational Databases	RI, RIA, EE	E
NSRAM	Agent Based, MC	RI, RIA, RP, RMP, EE	C, E, IT
PC Tides	Mathematical Equation	RI	D, ES, HPH, WWS
PFNAM	Network Based	RI, RIA	E
PipelineNet	Network Based, GIS, Relational Databases	RI, RIA, RMP	HPH, WWS
QualNet	Network Based, DS	RI, RIA	C
Restore	Empirical	RMP	CM ,E
R-NAS	Network Based	RI, RIA, RMP, EE	FA, TS
RTDS	Real Time Simulation	RI	E
SessionSim	Agent Based, DS	RI	C
SIERRA	Network Based	RI, RIA, RMP, EE	TS
TEVA	Empirical	RI, RIA, RP	HPH, WWS
TRAGIS	Network Based, GIS, Relational Databases	RI	TS, WWS
TranSims	Agent Based, DS	EE	CF, TS
UPMoST	Methodology (no modeling)	RI	CF
VISAC	System Dynamic Based	RI, RIA	CH, NRM
WISE	Agent Based, CS	RI, RIA, RMP, EE	CF, HPH, NRMW, WWS

Table 2. CIP tools classification

3. CIP MODELING TOOL COMPARISON

Critical Infrastructure Protection plans are mainly based on risk management frameworks, with NIPP being the most advanced program, not only in objectives, but also in strategies and references to other plans worldwide. Various countries have adopted similar CIP plans for the prevention and protection of CIs.

All tools are used by either internal or external analysts. An *external analyst* makes use of the analytical tools outside the developing organization, whereas an *internal analyst* uses them only internally. The classification criteria are related to the amount of expertise required in order to use the product, as well as the application requirements and the analytical output of each product. As far as requirements are concerned, criteria are driven by complexity, size and/or the nature of the underlying data used by each tool.

It should be stated here that, most tools were for in-house use only; thus, we did not manage to gather hands-on information. Information used for the classification and comparison has been taken from relevant bibliography, reports and published articles.

3.1 PURPOSE-BASED COMPARISON

By comparing the CIP tools based on which risk management stages are covering, useful insight can be provided: 76% of the tools are dealing with Risk Identification (RI) and 67% are covering Risk Impact Assessment (RIA). 42% provide some sort of Risk Prioritization (RP) and 41% of them provide Risk Mitigation Planning (RMP), while only 35% evaluates the Effectiveness (EE).

Results showed that covering all risk management stages is hard to achieve with a single tool, since it requires complicated data analysis. Only 4% (i.e., 3 tools) cover all five risk purpose stages, while 17% (i.e., 11 tools) cover four risk purpose stages. The other 80% of tools cover one, two or three stages, as depicted in Figure 6.

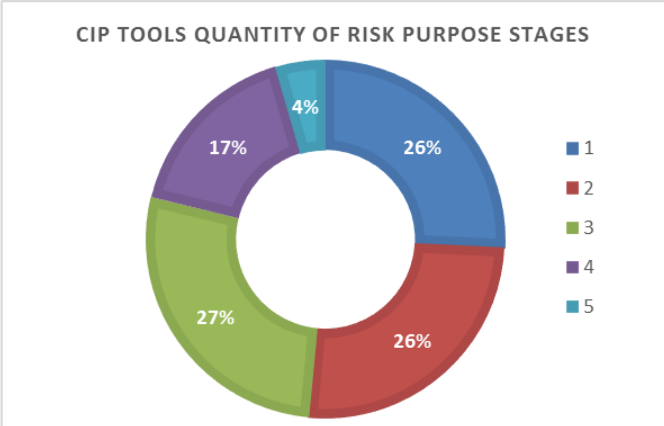

Figure 6. CIP tools per risk stages classification number

Tools that cover all five stages of risk purpose are less than 5%. Most of them are either broad methodologies (like COUNTERACT, IRRIIS, EURACOM, BIRR) or sophisticated tools, like NSRAM. The NSRAM is a complex network system simulation modeling tool, but is covering only three sectors (E, IT, C). Tools that can cover more than four risk purpose stages and more than 10 different sectors are limited (5%). Again, most of them are either broad methodologies as mentioned before or advanced tools developed in the US (e.g. CIMSuite, CIP/-DSS, CIPDSS-DM, Fort Future).

CIP/DSS [10] is a complete risk assessment methodology that can be applied to all sectors. It is developed by the National Infrastructure Protection Plan (NIPP). It is mostly used by military and government segments as a probabilistic optimization integrated system model that uses system dynamics as a modeling technique with continuous time-step simulation. Similar to CIP/DSS, the CIPDSS-DM tool has the same abilities but it is designed to facilitate analysts and policy makers in the evaluation and selection of the optimal risk mitigation strategies. All things considered, CIP/DSS - combined with CIPDSS-DM - is a robust critical infrastructure protection tool because it can be applied to all sectors as they are derived from NIPP. Moreover, the ability of CIPDSS-DM to facilitate in the selection of the most effective mitigation strategy is helpful not only in terms of restricting the impact of potential incidents, but also economic losses. Finally, its modelling (system dynamic based) seems more attractive for interdependency analysis, predicting responses and policy implementations.

Fort Future [8] was developed by the US Army Corps of Engineers. It is an agent-based tool that runs multiple dynamic simulations to evaluate a set of alternative scenarios. It supports GIS. It is unavailable for civilian applications and is only being used for military purposes.

CIMSuite [17] software enables users to run different scenarios. It can depict cascading effects on all sectors. It can also depict infrastructure relationships. It is a system-dynamic tool implementing a variety of algorithmic probabilistic simulations and incorporating the human response element into its physical infrastructure model. CIMSuite covers four (RI, RIA, RMP, EE) risk purpose stages. It is commercially available by the Idaho National Laboratories.

Athena [2, 7, 8], even though it only supports the Risk Impact Assessment stage, it can be used on a number of different sectors and it can also be used for studying the interdependencies between different CIs along with their potential cascading effects. We have distinguished it because it is the only tool that can create ontological models with certain abstraction characteristics. One of Athena's shortcomings is its need for extensive data concerning the network of CIs and their corresponding interdependencies. Athena is currently restricted and only provided to government and military users.

Concerning the stages of Risk Identification (RI) and Risk Prioritization (RP), two tools stand out due to their interesting output, CARVER 2 [18] which stands for Criticality Accessibility Recoverability Vulnerability Espyability Redundancy [9], and MUNICIPAL [19], which stands for Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines [13]. Both seem able to analyze multiple sectors of a CI, so as to identify the most critical components as well as prioritize them according to severity, i.e., the impact if a failure occurs in them. The approach, however, that each one of them uses is slightly different. CARVER2 [18] uses rating matrices which is the basis for the generation of hazard maps, whereas MUNICIPAL uses relation databases on asset inventories for networks in order to deal with as much information as possible for each asset that constitutes the critical infrastructure [13-15]. MUNICIPAL seems more efficient because it uses risk management techniques to identify risks, as well as because its output is based on GIS.

Other tools can also provide Risk Mitigation planning (RM), on top of RI and RP. Some other tools are IEISS [20] (Interdependent Environment for Infrastructure System Simulations) and IIM (Inoperability Input-Output Model). IEISS mostly addresses military and government segments [13]. It is suited for sectors like energy, water and wastewater systems, nuclear reactors material and waste, as it simulates their dynamic behavior, including interdependencies between systems [13-14,16]. IIM is a continuous input-output model developed by Sandia National Laboratories and Los Alamos National Laboratories and sponsored by the US Dept. of Homeland Security. It uses analytical models to determine the impact of an attack on infrastructure and its cascading effects in all interconnected infrastructures [16].

Both tools analyze energy, water and wastewater sectors. Also, both of them use continuous simulation and are mostly used for internal, in-house analysis. Furthermore, both are built for risk identification risk prioritization and risk mitigation planning purposes. On the other hand, their diversities are not few. IIM has a wider variety of sectorial coverage contrary to those supported by IEIIS. Moreover, IEISS uses multi-agent systems with Monte Carlo simulation as a supplementary technique for modeling, where IIM uses rating matrices and network theory with continuous time-step simulation in order understand the dynamic behavior of the infrastructure systems. As a result, IEISS can be applied to numerous sectors, and its ability to perform experiments using Monte Carlo simulation seems promising and valuable.

CIDA (Critical Infrastructure Dependency Analysis tool) [24-25] is a hybrid (empirical and network) based tool that extends a previous graph-based, risk analysis methodology to dynamically assess the evolution of cascading failures over time. It employs different growth models to capture slow, linear, and fast evolving effects, but instead of using static projections, the evolution of each interdependency between CIs is “objectified" by a fuzzy control system that considers the effect of near dependencies. To achieve this, the impact (and, eventually, risk) of each dependency is quantified on a time axis, in a form of many-valued logic. CIDA can analyze the last three stages of NIPP's Risk Assessment framework (RP, RMP, EE).

3.2 TECHNICAL APPROACH BASED COMPARISON

By comparing the modeling approach used by each tool along with the number of risk assessment stages covered, we have noticed that empirical based tools are mostly used to cover the first two risk management stages (RI, RP). Agent based tools are mostly popular for RI purposes, while network based approaches can cover three risk stages (RI, RIA, RMP). System dynamic and network based approaches are used mainly with tools that cover four risk management stages. These tools are quite few. Even fewer (i.e., 3) are the tools that cover all 5 risk purpose stages with no specific approach trend. This is depicted in figure 7, where the examined tools have been categorized according to their modeling approach in relation with number of purpose stages covered.

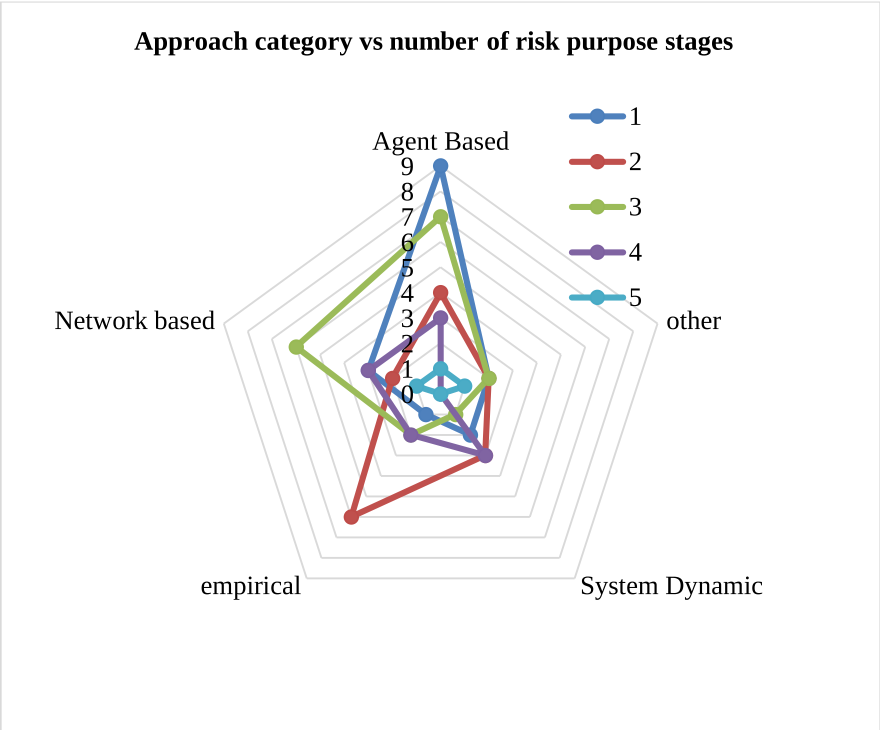

Figure 7. Modeling approach compared to number of risk purpose stages

CI modelling is mainly associated with simulation techniques and mathematical models, which are combined with the above mentioned supplementary computational techniques. Categorization according to the modeling approach used per number of sectors is presented in Figure 8. Agent based and network based tools are covering mainly up to three CI sectors. Only few tools and methodologies cover more than seven types of CI sectors. For tools covering 1-2 sectors, Energy, Transportation and/or Public Health sectors seem to be the most popular.

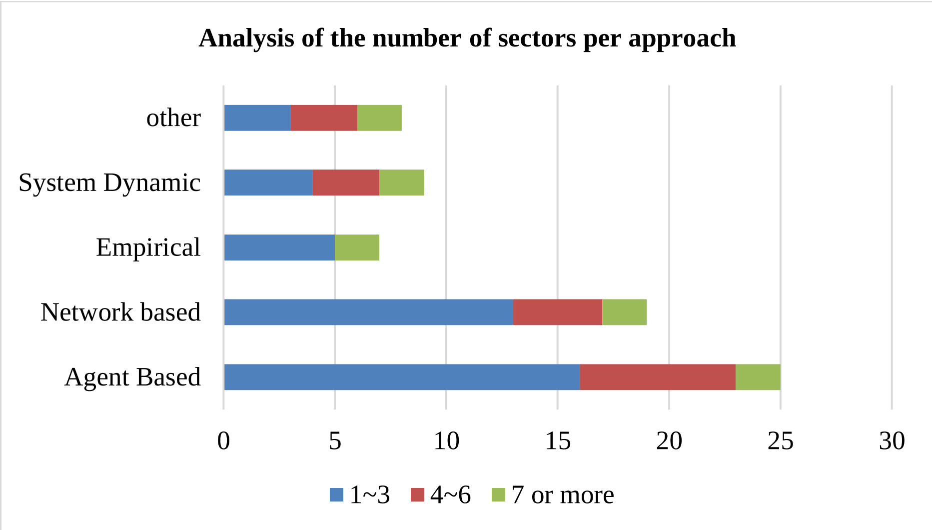

Figure 8. CIP tools classification per modeling approach and number of purpose stages

A wide acceptance of simulation paradigms exists, especially through modelling with the use of multi-agent systems, as well as of system dynamics, that are most commonly combined with the computational methods of Monte Carlo simulation, discrete time-step simulation, and continuous time-step simulation, as they are most suitable for optimal solutions [2,7,12]. There are also other applications of agent-based simulation, which are combined with Geographic Information Systems (GIS) in order to predict not only human behavior, but also the performance of the infrastructure in case of an emergency within specific geographic areas.

Relational databases, on the other hand, are currently the predominant choice in order to store data, information and records which represent the properties of a system in a precise manner. Thus, relational databases are widely used in asset inventorying which can be combined with monitoring of events, real time recording, GIS, error logs, access control, risk components, etc. By doing this, it is easier to establish relationships among elements that compose the critical infrastructure, just by matching data using common characteristics found within the data sets.

What is more, rating matrices are useful in assessing the severity of a risk, when an event occurs, through and decision making procedure. These kind of modelling techniques not only include data processing in risk analysis and risk mapping to support decision making, but also make use of traditional techniques. They are popular due to the fact that they allow combination with every computational technique and also have the ability to facilitate on sensitivity analysis. Last, but not least, rating matrices are appropriate for data classification of GIS, as well as of monitoring events, because they may contain weighted data.

As far as network theory is concerned, it makes feasible to identify the most critical nodes of an infrastructure by using graphical models that refer to the properties of the system in a precise manner. The complexity of network theory models, however, can increase exponentially for large infrastructures. Thus, these models are applicable for smaller systems.

The majority of tools are dedicated to a specific sector (or 1-2 similar sectors) (39 out of 68 tools), with Energy and Transportation sectors being the most popular ones. NG Analysis Tools, EPRAM, FEPVA and RTDS [22] are dedicated to the Energy Sector. NG Analysis Tools is an agent-based suite covering three purpose stages (RI, RIA, EE). FEPVA [21] is a network-based tool that covers two purpose stages (RI, RIA). EPRAM differentiates by being the only cellular automata modeling tool. EPRAM (Electric Power Restoration Analysis Model) calculates potential restoration times for electric power systems and determines the time point when restoration needs to start. Restoration results used in EPRAM are based on cellular automata models and industry data. This is a specific type of analysis that models each sector individually, since cellular automata have two possible values for each cell (0, 1) and rules that depend on nearest neighbor values. The Real Time Digital Simulator (RTDS) [22] tool provides simulation of power systems technology. It is used to study power systems with complex High Voltage networks. Since the simulator functions in real-time the power system algorithms are calculated quickly enough to continuously produce output conditions, which realistically represent conditions in a real network.

Some tools are only dedicated to the Transport Sector, namely ATOM, SIERRA, Fast-Trans and AIMSUN [14]. Among them, ATOM and SIERRA [23] cover more than four risk purpose stages and they are both implement network-based method approaches. FastTrans is an agent-based tool that covers three purpose stages (RI, RIA, RPR).

AIMSUN is the only European Union originated tool and covers two purposes (RIA, RM). Each analysis approach is based on system dynamics. Europe has developed mainly methodologies (COUNTERACT, EURACOM, IRRIIS) and not full simulation tools. AIMSUN is the only Transport Simulation tool developed in Spain. Its analysis approach is based on system dynamics. The tool is able to cover two purpose stages (RI, RPR) but only for Transportation.

A meta-tool has been developed in the US, namely SimCore. It combines multi-agents as its modelling technique with discrete time-step simulation. It utilizes a collection ("family") of simulation applications (ActivitySim, DemandSim, SessionSim, FastTrans and MIITS-Net-Sim) All of them follow the SimCore modelling paradigm as a library for building large-scale distributed-memory discrete event simulations and can work together by exchanging events.

4. CONCLUSIONS

As shown, CI modeling and analysis tools, frameworks, and methodologies mainly focus on the study of large-scale infrastructures, their states, and potential dependency scenarios. The primary goal of these tools is to help risk assessors and CIP decision makers to assess CI risks. Risk assessors may project potentially damaging failures and thus detect risks, dependencies and possibly provide alternatives and countermeasures. Some tools can also be used for the proactive assessment of risk mitigation controls and therefore, help increase resilience in CIs.

In this paper we have presented the results of a review of currently available tools, frameworks and methodologies that are able to model CI characteristics, their interdependencies and the impact of potential failures in their systems. In particular, we created a taxonomy of detected tools and methodologies using widely accepted classification systems. We have identified, classified, and compared various tools that have been developed to analyze CIs and support CI risk management. Emphasis has been given on the comparison of similar tools from the perspective of their purpose and modeling approach.

Most Critical Infrastructure Protection plans have been based on risk management frameworks. USA/NIPP keeps the most advanced program in developing strategies, techniques and applications. In general, the classification and comparison is broken into two distinct stages:

- The first one uses purpose stages to obtain a clearer view of the goals attained and the functionality of each classified CI tool. Literature review identified the models used for each stage of risk assessment and mitigation and showed that most tools focus on the risk identification and risk assessment stages.
- The second part of this faceted classification, categorized tools using their technical modeling approaches. Most tools utilize and possibly merge multi-agent systems approaches with system dynamics, network theory and/or empirical systems. Our classification and comparison showed that multi-agent and network based systems are the most widespread modeling techniques in among tools.

We found that no tool can be seen as a “jack-of-all-trades” and that most tools specialize in specific section of the Risk Management process. The information presented is however not yet able to provide an extensive overview of all tools and methodologies due to the fact that many tools are built for in-house use only.

The effective implementation of the CIP plans depends on the degree to which government and private sector partners engage in systematic, effective, multi-directional information sharing. We recommend that future research and tools should address the latter stages of the Risk Assessment framework (RMP, EE) and either put more attention on developing holistic approaches that can model all CI sectors, or focus entirely on specific problems in specific sectors to maximize contribution.

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APPENDIX:

CIP TOOLS AND METHODOLOGIES:

TOOL	DEVELOPER	ORIGIN	DESCRIPTION	SECTOR	WEB LINK
ActivitySim	Los Alamos National Laboratories	USA	Activity representation of the US population	CF	http://public.lanl.gov/sunil/pubs/simx.pdf
AIMS (Agent-based Infrastructure Modelling and Simulation)	University of New Brunswick	CAN	Interdependency modeling and survivability of Canada's CIs	E, C, WWS, IT	http://ebagheri.athabascau.ca/papers/ijbpim.pdf
AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks)	Transport Simulation Systems	ESP	Traffic modeling	TS	https://www.aimsun.com/
AMTI (Advanced Modeling & Techniques Investigation (Loki Toolkit)	Sandia National Laboratories	USA	Quick formulation and application of network models of complex systems	E, TS, FS	http://www.sandia.gov/casosengineering/amti.html
AT/FP (Anti-Terrorism/Force Protection)	Naval Postgraduate School	USA	Planning waterside security for ships in a port	DIB, ES, HPH, TS	https://savage.nps.edu/RobotTelemetry/DonCioXmlWgNpsSlides/NPSATFPProjectFlyer.2007Apr19.pdf
Athena	On Target Technologies, Inc.	USA	Interdependency modeling and analysis	C, CF, CM, DIB, E, FS, IT, NRMW, WWS, TS	https://inldigitallibrary.inl.gov/sti/3489532.pdf
ATOM (Air Transportation Optimization Model)	Sandia National Laboratories / Los Alamos National Laboratories	USA	Consequence assessment of a partial or complete outage at a major airport for an extended period of time	TS	http://www.sandia.gov/nisac/capabilities/network-optimization-models/
BIRR (Better Infrastructure Risk and Resilience)	U. Dept. of Homeland Security	USA	Vulnerabilities assessment and risk reporting	All sectors	http://www.dis.anl.gov/projects/ri.html
CAPRA (Comprehensive Approach for Probabilistic Risk Assessment)	CEPREDENAC sponsored by World Bank & UN	Latin America	RVA tool for assessing, understanding and communicating disaster risk	WWS, HPH, TS, FS	www.ecapra.org/
CARVER 2 (Criticality Accessibility Recoverability Vulnerability Espyability Redundancy)	National Infrastructure Institute, Center for Infrastructure Expertise	USA	Threat and potential terrorist targets prioritization	HPH	http://ec.europa.eu/home-affairs/doc_centre/terrorism/docs/RA-ver2.pdf
CASCADE	DNV (Det Norske Veritas)	Norway	Analyzation of catastrophic disruptions of large, interconnected infrastructure systems due to cascading failures	All sectors	
CI^3 (Critical Infrastructure Interdependencies Integrator)	Argonne National Laboratories	USA	Emulation of time and cost needed for restoration purposes	C, CM, E, NRMW, WWS	http://www.ipd.anl.gov/anlpubs/2002/03/42598.pdf
CIDA (Critical Infrastructure Dependency Analysis tool)	INFOSEC Lab, Athens University of Economics & Business	EU	Dynamic assessment of the evolution of cascading failures over time. Interdependency analysis and risk mitigation.	All sectors	https://github.com/geostergiop/CIDA/wiki/
CIMS (Critical Infrastructure Modeling System)	Idaho National Laboratories	USA	Visualization of cascading consequences of infrastructure perturbations	C, CF, E, TS, HPH	https://inldigitallibrary.inl.gov/sti/3578215.pdf
CIMSuite: Critical Infrastructure Modeling	Idaho National Laboratories	USA	Preparation for man-made and natural disasters	All sectors	http://www4vip.inl.gov/factsheets/docs/cimsuite.pdf
CIP/DSS (Critical Infrastructure Protection Decision Support System)	LANL, SNL, Argonne National Laboratories	USA	Dynamic simulation of individual infrastructures	All sectors	http://www.systemdynamics.org/conferences/2005/proceed/papers/LECLA332.pdf

CIPDSS-DM (Critical Infrastructure Protection Decision Support System Decision Model	LANL, SNL, Argonne National Laboratories	USA	Decision making proposal under conditions of uncertainty and risk	All sectors	http://www.ipd.anl.gov/anlpubs/2008/12/63060.pdf
CIPMA (Critical Infrastructure Protection Modeling and Analysis)	Government of Australia	Australia	Critical infrastructure resilience enhancement	C, E, IT, TS, FS	http://www.polymtl.ca/crp/doc/GREGSCOTT-CIPMABriefingforCanada.pdf
CISIA (Critical Infrastructure Simulation by Interdependent Agents)	University of New Brunswick	CAN	Interdependency and system analysis	C, CM, E, WWS, C	http://www.chiarafoglietta.com/wp-content/uploads/2015/04/Cisia.pdf
CommAspen (Agent-based simulation model of the US economy)	Sandia National Laboratories	USA	Simulation of interdependent effects of market decisions and disruptions in the telecommunications infrastructures	FS, C, E	http://www.inf.uniroma3.it/autom/LabRob/Projects/CISIA/home.html
Counteract (Generic Guidelines for Conducting Risk Assessment in Public Transport Networks)	International Association for Public Transport	EU	Risk reporting	TS, E, HPH	http://www.transport-research.info/sites/default/files/project/documents/20120719_145438_7577_COUNTERACTGuidelines_lr.pdf
DECRIS (Risk and Decision Systems for Critical Infrastructures)	SAMRISK Project	Norway	All-hazard generic RVA methodology suitable for cross-sector infrastructure analysis	E, WWS, TS, C, IT	https://www.sintef.no/projectweb/samrisk/decris/
DemandSim	Los Alamos National Laboratories	USA	Geographically demand computation on each of the CI sectors	All sectors	http://www.lanl.gov/
EMCAS (Electricity Market Complex Adaptive System)	Argonne National Laboratories. Sponsored by Adica Consulting	USA	Simulation of complex power systems for operational and economic impact consequence calculation	E	http://www.energyplan.eu/othertools/national/emcas/
EpiSimS	Los Alamos National Laboratories	USA	Analyzation of disease spread in the US	HPH	http://public.lanl.gov/sdelvall/p556-mniszewski.pdf
EPRAM (Electric Restoration Analysis Tools	NISAC	USA	Impact determination of network-level damage on electric power restoration	E	http://www.mssanz.org.au/modsim2013/D2/stamber.pdf
EURACOM (European Risk Assessment and Contingency Planning Methodologies for Interconnected Energy Networks)	EU/DG for Enterprise & Industry	EU	Contingency planning	All sectors	http://cordis.europa.eu/result/rcn/53099_en.html
FAIT (Fast Analysis Infrastructure Tool)	Sandia National Laboratories. Sponsored by US Dept. of Homeland Security	USA	Economic analysis tool for conducting economic impact assessment across multiple sectors	E, ES, FS, TS, WWS	http://www.sandia.gov/casosengineering/docs/Stochastic%20Mapping%20of%20Food%20Distribution%202011%20NGI%20conference.pdf
FastTrans	Los Alamos National Laboratories	USA	Route simulation of vehicles on real-world road networks	TS	http://www.lanl.gov/programs/nisac/fasttrans.shtml
FEPVA (Framework for Electricity Production Vulnerability Assessment)	Los Alamos National Laboratories	USA	Impact assessment of natural disasters or malicious attacks for both response and preventative purposes	E	http://www.lanl.gov/
FINSIM (Financial System Infrastructure)	Los Alamos National Laboratories	USA	Modeling of cash and barter transactions that are dependent on contractual relationships and a network at the federal reserve level	FS, E, C	http://cnls.lanl.gov/annual26/abstracts.html
Fort Future	US Army Corps of Engineers	USA	Simulation for testing plans for Dept. of Defense installations	C, CF, CM, E, ES, FS, HPH, IT, NRMW, TS, WWS	http://www.usace.army.mil/
HCSim (Healthcare Simulation)	Los Alamos National Laboratories	USA	Impact assessment of mass-casualty incidents on hospital capacity	D, HPH, NRMW	http://www.osti.gov/scitech/biblio/1084564
HURT (Hurricane Relocation Tool)	Los Alamos National Laboratories	USA	Hurricane relocation	HPH	http://www.lanl.gov/

HYDRA Population & Economic Modeling	Los Alamos National Laboratories	USA	Development of a service-oriented architecture for integrated Web-based access of LANL agent-modeling capabilities	HPH, FS	http://www.bwbush.io/projects/hydra.html
I2SIM (Infrastructures Interdependencies Simulation)	University of British Columbia	CAN	Simulation of a disaster response scenario at the system level, showing the impacts of the events that occur	CF, TS, CM, HPH	http://www.ece.ubc.ca/~jiirp/
IEISS (Interdependent Environment for Infrastructure System Simulations)	University of Virginia	USA	Electric power flow model that simulates service & outrage areas, outrage duration and critical system components	E, TS, WWS	https://inldigitallibrary.inl.gov/sti/3489532.pdf
IIM (Inoperability Input-Output Model)	Sandia National Laboratories and Los Alamos National Laboratories	USA	Analyzation of economic impacts	FS, E, C, IT, TS, FS	https://inldigitallibrary.inl.gov/sti/3489532.pdf
IntePoint VU	Intepoint LLC	USA	Analyzation of complex environments and modeling system-wide interdependencies across physical, virtual and social networks	C, E, CF, TS	http://intepoint.com/products/index.html
IRRIIS (Integrated Risk Reduction of Information-based Infrastructure Systems)	IRRIIS Project	EU	Interdependency analysis and management of CI	All sectors	http://www.irriis.org/
Knowledge Management &Visualization	Carnegie Mellon University	USA	Analyzation of vulnerabilities associated with delivery of fuel	E, TS, WWS	https://inldigitallibrary.inl.gov/sti/3489532.pdf
LogiSims	Los Alamos National Laboratories	USA	Planning preparation for a disaster and real-time response to a disaster	HPH, E	http://public.lanl.gov/rbent/bent-pes.pdf
LS-DYNA	Livermore Software Technology Corporation	USA	Behavior analysis of structures as they deform and fail	CM, D, TS	http://www.lstc.com/products/ls-dyna
MBRA (Model-Based Risk Assessment)	Naval Postgraduate School, Center for Homeland Defense & Security	USA	Resilience analyzation of the crude oil pipeline network	FS, TS, E	https://www.chds.us/ed/items/2164
MIITS (Multi-Scale Integrated Information & Telecommunications System)	Los Alamos National Laboratories	USA	Realistic simulation of internet packet traffic on a national or global level	C, IT	http://www.lanl.gov/programs/nisac/miits.shtml
MIN (Multi-layer Infrastructure Networks)	Purdue University	USA	A Simulation tool of automobile, urban freight and data network layer	CF, TS	https://inldigitallibrary.inl.gov/sti/3489532.pdf
MSM (MIT Screening Methodology)	Massachusetts Institute of Technology	USA	Prioritization of vulnerabilities	E, WWS, HPH	
MUNICIPAL (Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines)	Rensselaer Polytechnic Institute	USA	Interdependency analyzation of civil infrastructure systems	E, C, IT, TS	http://eaton.math.rpi.edu/faculty/Mitchell/papers/decisiontechnologies.pdf
N-ABLE (National Agent-Based Laboratory for Economics)	Sandia National Laboratories and Los Alamos National Laboratories	USA	Analyzation of economic factors, feedbacks and downstream effects of infrastructure interdependencies	E, FS, TS	http://www.sandia.gov/nisac/capabilities/nisac-agent-based-laboratory-for-economics-n-able/
NEMO (Net-Centric Effects-based Operations Model)	Sparta, Inc.	USA	Modeling of cascading effects of events across multiple infrastructure networks	C, E, WWS, TS, DIB	http://www.dodccrp.org/events/10th_ICCRTS/CD/papers/128.pdf
Network-Centric GIS	York University	USA	Decision making proposal using GIS interoperability	TS, WWS, ES	https://inldigitallibrary.inl.gov/sti/3489532.pdf
Nexus Fusion Framework	IntePoint, LLC	USA	Visualization of intended and unintended effects and consequences of an event across multiple infrastructure models	E, C, TS, DIB	https://inldigitallibrary.inl.gov/sti/3489532.pdf
NGAT (Natural Gas Analysis Tools)	Argonne National Laboratories	USA	Modeling of the natural gas pipeline infrastructure	E	https://inldigitallibrary.inl.gov/sti/3489532.pdf
NSRAM (Network Security Risk Assessment Model)	James Madison University	USA	Analyzation of large interconnected multi-infrastructure networks to determine how the systems respond and interact to various accidents and attacks	E, IT, C	http://www.jmu.edu/iiia/wm_library/NSRAM_Application_to_Municipal_Electric.pdf

PC Tides	Neptune Navigation Software	UK	Wind speed and flood surge analysis	HPH, ES	http://www.neptunenavigation.co.uk/tides.htm
PFNAM (Petroleum Fuels Network Analysis Model)	Argonne National Laboratories	USA	Hydraulic calculations of pipeline transport of crude oil and petroleum products	E, TS	http://www.gss.anl.gov/publications-2/
PipelineNet	EPA	USA	Hydraulic and water quality models integration using existing databases for providing emergency managers real time information and for estimating the risks to public water supplies	WWS, HPH	http://files.waterky.org/aamastrrefs/Bahadur%20et%20al.%202003.%20PipelineNe.%20a%20model%20for%20monitor%20introd%20contam%20in%20a%20dist%20syst.%20World%20Water%20Congr.%202003..pdf
QualNet	Scalable Network Technologies, Inc	USA	Telecommunication analysis	C	http://web.scalable-networks.com/
Restore	Argonne National Laboratories	USA	Estimation of time and cost needed to achieve an intermediate stage of completion, as well as overall completion of a goal	CM, E	http://www.anl.gov/egs/group/resilient-infrastructure/resilient-infrastructure-capabilities
R-NAS (Railroad Network Analysis System)	Sandia National Laboratories and Los Alamos National Laboratories	USA	Studying and understanding the flow of commodities over the US rail infrastructure	FA, TS	http://www.sandia.gov/nisac/capabilities/network-optimization-models
RTDS (Real Time Digital Simulator)	RTDS Technologies	Canada	Testing the dynamic behavior of the power systems in real time	E	https://www.rtds.com/
SessionSim	Los Alamos National Laboratories	USA	Generation of data traffic between communication of individuals	C	http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=5429274&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5429274
SIERRA (System for Import/Export Routing and Recovery Analysis)	Sandia National Laboratories and Los Alamos National Laboratories	USA	Flow diversions estimations between US ports	TS	http://www.sandia.gov/nisac/tag/system-for-importexport-routing-and-recovery-analysis/
TEVA (Threat Ensemble Vulnerability Assessment)	EPA	USA	Vulnerability assessment of a water utility to a large range of contamination attacks	HPH , WWS	http://ascelibrary.org/doi/abs/10.1061/40737%282004%29482
TRAGIS (Transportation Routing Analysis Geographic Information System)	Oak Ridge National Laboratories	USA	Calculation of highway, rail or waterway routes in the US	TS, WWS	http://web.ornl.gov/sci/gist/TRAGIS_2005.pdf
TRANSIMS (Transportation Analysis Simulation System)	Los Alamos National Laboratories	USA	Evaluation of transportation consequences of urban evolution scenarios. Simulation of every vehicle movement through a large metropolitan area	TS, CF	https://code.google.com/p/transims/
UPMoST (Urban Population Mobility Simulation Technologies)	NISAC	USA	Provides the common interface for the flow of information between multiple UIS domain-specific models	CF	https://scs.org/magazines/2012-01/index_file/Files/MoonAndLee.pdf
VISAC (Visual Interactive Site Analysis Code)	Oak Ridge National Laboratory	USA	Prediction and analyzation of outcomes of different accidents/incidents at various nuclear and industrial facilities	CH, NRMW	http://computing.ornl.gov/cse_home/about/VISAC_FactSheet.pdf
WISE (Water Infrastructure Simulation Environment)	Los Alamos National Laboratories	USA	Evaluation of water infrastructure, in terms of both infrastructure specific and interdependency issues	CS, TS, WWS, HPH	http://cedb.asce.org/cgi/WWWdisplay.cgi?146772