Rapport

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Complex Dependencies Analysis

Technical description of complex dependencies in Critical Infrastructures, i.e. smart grids.

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Editor: Yuning Jiang

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Authors:

Yuning Jiang (University of Skövde)

Jianguo Ding (University of Skövde)

Yacine Atif (University of Skövde)

Manfred Jeusfeld (University of Skövde)

Sten Andler (University of Skövde)

Birgitta Lindström (University of Skövde)

Christoffer Brax (Combitech)

Daniel Haglund (Combitech)

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EXECUTIVE SUMMARY

This document reports a technical description of ELVIRA project obtained as part of Work-package 2.1 entitled “Complex Dependencies Analysis”. ELVIRA project is a collaboration between researchers in School of IT at University of Skövde and Combitech Technical Consulting Company in Sweden, to investigate critical infrastructures cybersecurity.

The development of digital and communication technologies, have transformed critical infrastructures operations into interconnected systems with increased degree of cyber-threat exposures. Thus, new vulnerabilities emerged due to IT systems that monitor dependencies across critical infrastructure components. For example, monitoring supply-demand balance across dependent power-components in smart-grids. Subsequently, much attention has been given to model complexities induced by dependencies between components of systems by elaborating models that capture disturbance consequences caused by potential cyber-attacks, at a chosen abstraction level.

Recent researches have attempted to unearth complex connections among critical infrastructure components. In this technical report, we review these attempts where connections are regarded as influencing factors to IT systems monitoring critical infrastructure, based on which potential dependencies and resulting disturbances are identified and categorized. Each kind of dependence has been discussed based on our own entity based model. Among those dependencies, logical and functional connections have been analysed with more details on modelling and simulation techniques.

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1. Introduction

Defined as a network of components and physical flows that produce and distribute essential goods and services to society, an infrastructure system is considered to be “critical” if a disruption in components’ operation or flow balances cause a debilitating impact on vital societal systems (PCCIP, 1997). Although the importance of Critical Infrastructures (CIs) has received a close attention in the literature, research on Critical Infrastructure Protection (CIP) and robust monitoring-system design faced challenges, partly induced by the complexity of such systems.

Physical structures of CIs are developed as a complex network of components with interconnections spanning the physical CI topology. One example of CI would be the power-grid supporting vital societal systems with electricity supply. This physical structure of a typical CI is naturally decentralized spanning geographically-distributed locations, and monitored by modern IP networks and control systems such as SCADA. Typical power components may include distributed energy resources involving generators, transmission-lines and power-loads. The usage-scheduling of these resources require appropriate management provided by IT systems that monitor the whole grid (Lezama et al., 2017). Framework that identify dependencies among CI components falls under this managerial system to unearth indirect responsibilities of cascading failures threatening CI’s resilience.

Interesting works in this interdisciplinary field showed a promising progress towards eliciting dependency chains across CIs. A pioneering paper from (Rinaldi et al., 2001) proposed a classification of critical infrastructures defined as highly interconnected and mutually dependent components in complex ways, both physically and through a host of so-called "cyber physical based systems" which defines the interdependence nature linking physical- and cyber-CIs. In their further works, they showed a trend in the exploration of modelling methodologies and simulation techniques involving such interdependencies (Rinaldi et al., 2011). Different metrics were thereafter proposed to evaluate the degree of these interdependencies in order to categorise their implications across a range of CIs, for example the range of involved societal sectors, such as industrial, food or health sectors (Zimmerman, 2001; Dudenhoeffer et al., 2006; Vespignani, 2010; Zhang and Peeta, 2011; Setola et al., 2014). Although increasing efforts have been made in addressing the importance of dependencies within CIs and interdependencies with monitoring cyber-systems or other CIs, considerable attempts in analysing the direct or indirect influence of one CI entity on another, and the extent of these influences in terms of spatial/temporal dimensions are still unclear. In addition, systematic methodologies to analyse the inherent level of dependencies and interdependencies, as well as the potential damages to societal functions are increasingly investigated.

In conclusion of this brief motivational introduction, a conceptual model that bridges heterogeneous CI components, and simulation tools that evaluate the coherence of dynamic exchanges that occur within and across CI boundaries are leading the prospects for research into identifying influential CI network elements which vulnerability could incur higher damage implications. The evaluation of CI topology and the analysis of flow dynamics are vectors for CI efficiency, robustness and resilience.

The following research questions drive the subsequent sections of this document:

- How to identify and then classify the connections within and among CIs?
- How to distinguish CI dependencies and interdependencies?
- What are the types of CI dependencies and interdependencies?
- How to analyse different types of dependencies and interdependencies? Could those analysis be made in one simulator?
- What modelling and simulation approaches are used for investigating influential components in dependency and interdependency networks? What are their advantages and disadvantages?

The risk of losing the holistic-view by only considering the micro side of CIs, or making assumptions over uncertain details at the macro level of CIs, reduce the accuracy of CI dependency analysis (Carhart and Rosenberg, 2016). In this technical report, consideration is given to both micro-level and macro-level of CI networks, to convey an accurate degree of situation awareness.

2. Background and Concepts Definition

A range of vocabulary and concepts are used in CI dependency networks analysis. Next we provide some definitions that are relevant to the background of this report.

2.1. CI Networks

CI networks could be modelled as a graph of interacting components across physical and cyber dimensions (Yagan et al., 2012). In this modelling approach, a distinction is made between inter-edge and intra-edge junctions. Graph edges linking components within the same dimension refer to intra-edges whereas those connecting components across dimensions are labelled as inter-edges. The inter-edges and the intra-edges within and across CIs could be explored considering the topology of interconnected networks as illustrated further in Figure 1. This multi-dimensional perspective of interdependency is in agreement with the mutual dependency among different CIs discussed in (Luiijf et al., 2008). Liu et al. conceive CI networks as large-scale distributed cyber-physical systems (CPSs) which incorporate cyber and physical CI domains. These two domains are connected to each other, and would be vulnerable to cascading-effects across both domains. Figure-1 shows an example of CPS based structures adopted in smart power-grids. In total there are three layers in smart grid, which are physical layer, control layer and information layer.

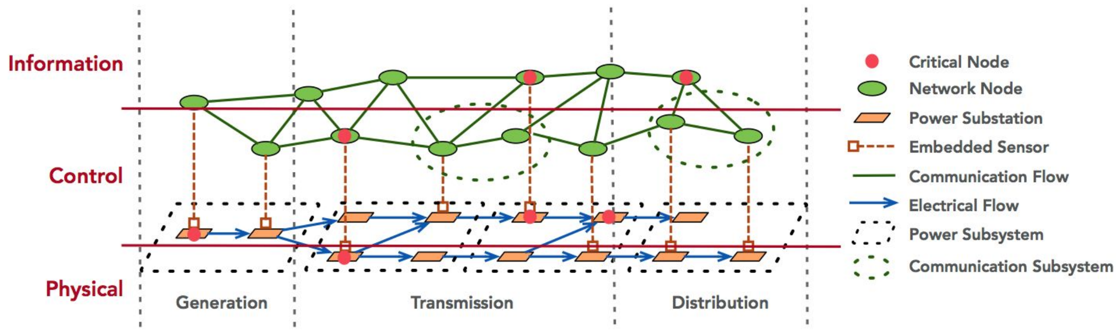

Figure-1. Multidimensional network illustration in smart power-grid structure

2.2. Complex Systems

Complex systems address the complementary process of interdependency physical, cyber and mediating CPS levels as illustrated further in Figure-2. Most of the existing interdependency modelling approaches are complementary instead of competing each other another, and a hybrid methodology to interoperate these modelling approaches is shown to provide appropriate insights (Satumtira and Dueñas-Osorio, 2010).

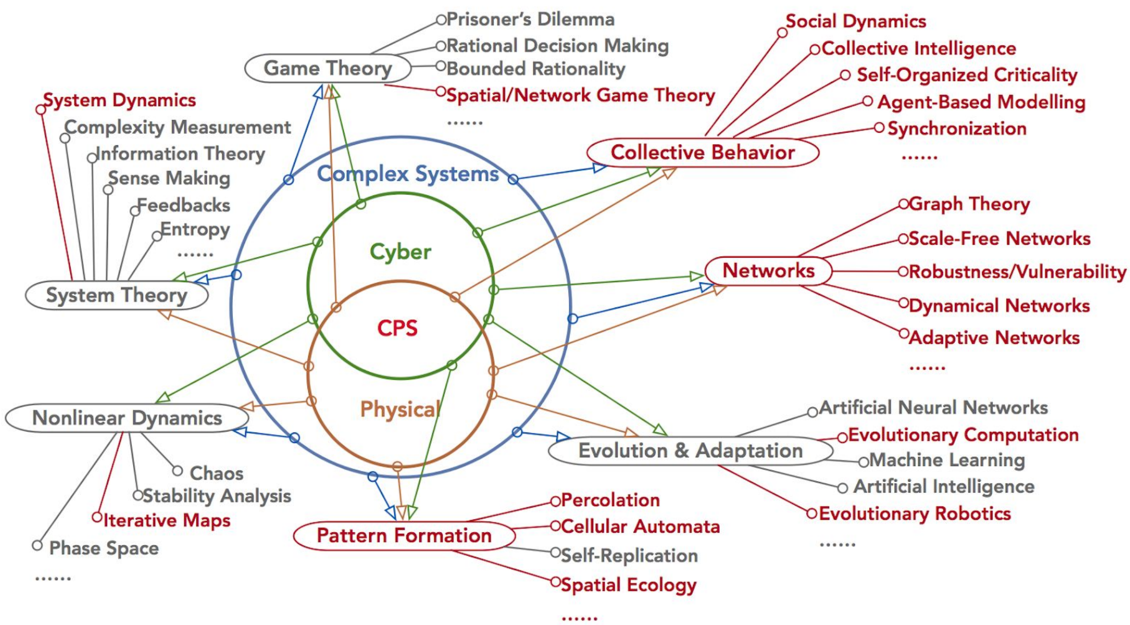

Figure-2. Complex Systems Theoretical Framework

2.3. Event, Fault and Failure

An event is a point in time where some conditions become true, e.g. detection of a component fault. However, the abnormal behaviour of component is a fault, e.g. a short-circuit causes the current to bypass the normal load. When a fault arises, it might lead to an exceptional behaviour of a component, and if not handled, the implications can propagate leading to a failure. Subsequently, the affected system deviates from its normal behavior. Failures are observed, e.g. by reading signals. A failure typically means that the component is in a “faulty” state. A failure may be passed across inter-connected components leading to a cascading failure phenomenon.

2.4. Cascading Effect

A cascading effect indicates that the disruption in one component causes the subsequent disruption in the connected components. A failure in one component can initiate cascading effects within an infrastructure or, in the worst case, cause failures in other infrastructures, possibly disrupting vital services. Such cascades of failures could disrupt both power and data-communication flows (Crucitti et al., 2004).

3. Dependencies: Definition and Analysis

3.1. Dependence and Interdependence Definitions

In order to clarify the boundaries of connected systems, concept definitions and modelling CIs are essential. In this document, CI is defined by a system which includes an entity with property variables, boundaries and communication capability with the external environment. In system theory, the general properties of systems are analysed regardless of their physical nature (Zadeh, 1962). A system could be defined as "*an object in which variables of different kinds interact and produce observable signals*" (Ljung, 1998).

Since a CI component could be regarded as an entity, all the connections between the internal system and the external environment could be divided into five property categories: input flows, output flows, measurable disturbances, unmeasurable disturbances, and feedback to the system itself. This entity-base model is further presented in Figure-3. Classifying connections into these five attributes would make it easier to build mathematical models of systems and their dependencies. These five connections are discussed further below.

- Input flows are prerequisites for the system to work in a normal status. Their forms (physical and/or cyber), patterns and threshold values are usually measurable and predictable. For example, the components in a power grid substation would require power inputs and certain control information to change or to maintain a working status.
- Output flows are prerequisites for other connected systems to work properly.
- Disturbances could change and break the working status of a system, and could trigger a failure. A system could contribute both as a receiver and a sender of disturbances.
    a. For measurable disturbances, their forms (mostly geographical and sometimes logical, or physical, or cyber) and patterns could be quantified in an abstract level, but not thoroughly analysed in current research due to their dynamic nature. For instance, a remote flood could cause the breakdown of some water pipes and drown the nearby power-lines and telecommunication lines, which could trigger failures

in the whole power-supply system and/or the communication network. Data about locations of the piping network, energy supply network and communication network could be accessed in advance, and therefore could be used in geographical disturbance analysis.

b. For unmeasurable disturbances, they are difficult to quantify. Taking the influence from power market to the power grids as an example, the collective behaviors from the dynamic society are intrinsically not easy to model because of their nonlinearity and interactions. Hence, correlations (positive or negative) between the disturbances and the system are normally identified on a qualitative level.

- Feedback consists in generated signals that are sent back to the system itself.

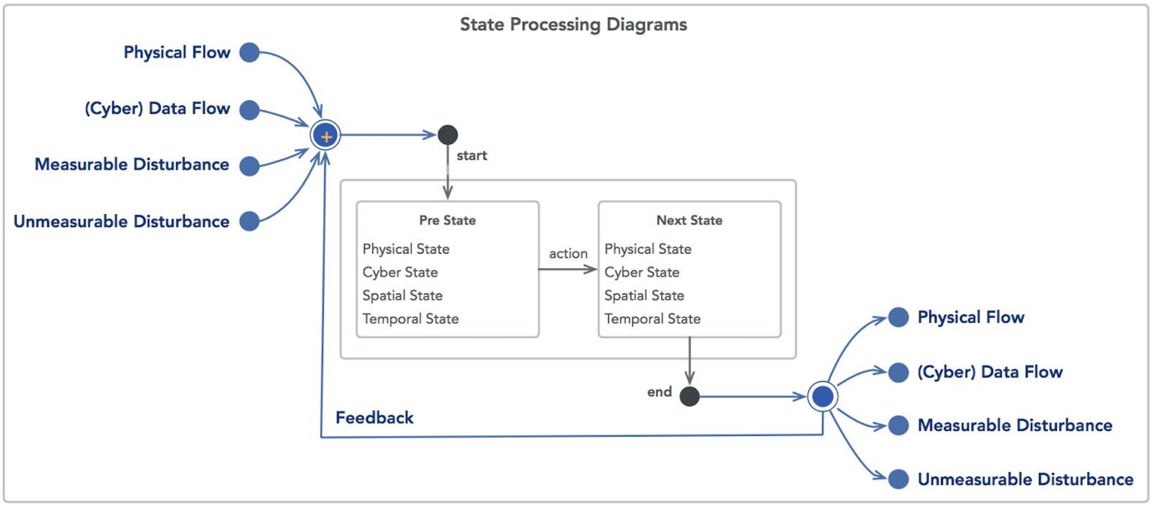

Figure-3. Entity Based State Diagram of Dependent Systems

From the above definitions of the five attributes, the differences between dependencies and other connections are based on the level of closeness and degree of dependency. Functional input/output attributes trigger direct state transformation. In comparison, disturbance attributes affect the state of the system indirectly.

Here, *dependency* is critical unidirectional connections between two or more entities (A, B, C,...) inside a system, i.e. entity A's status transition and/or maintained status are depending on such direct connections with the entity B, or the status of entity A is directly controlled by the entity B through such connections. For instance, in a smart-grid system, the status of a substation is directly influenced by the power flow from the physically-connected transmission substation, and also directly influenced by the data flow from the cyber-connected control system.

Interdependency refers to the critical bidirectional connections between two or more systems (A, B, C,...), i.e. system A's status transition and/or maintained service are depending on or controlled by such direct connections with the system B, and vice versa. For example, on one hand, an electricity supply system works properly with some supporting systems, including cooling system supported by the water supply system, and oil provided by oil and gas supply system. On the other hand, water supply system as well as oil and gas supply system could only work with electrical supplies..

Apart from critical connections such as dependency and interdependency, other non-critical relationships that could affect status of a system are named as *disturbances*. Disturbances are mostly bidirectional relationships.

3.2. Dependency and Interdependency Classification

Recent research has attempted to analyse the complicated relationships between at least two CIs. Based on the definition of interdependency as "a bidirectional linkage or connections between two infrastructures" through which the status of one infrastructure could influence or be influenced by the status of the other one, Rinaldi divided the types of interdependence into four main categories which are *physical interdependence*, *geographical interdependence*, *logical interdependence* and *cyber interdependence* (Rinaldi et al., 2001). Similar categories containing the four interdependencies proposed by Rinaldi have been investigated by Setola and also Vespignani (Setola et al., 2014; Vespignani, 2010). Influences from human and organizational factors have been valued with new concepts of interdependencies, such as *policy interdependencies, budgetary interdependency* and *economic interdependencies* (Dudenhoeffer et al., 2006; Dudenhoeffer et al., 2006). A further classification considers *functional interdependencies* and *spatial interdependencies* for the purpose of functional modelling (Zimmerman, 2001). Other classifications consider *geospatial interdependencies* and *information interdependencies* (Dudenhoeffer et al., 2006).

Some other research efforts to evaluate different interdependencies levels. For example, system interconnections are classified by Wallace et al. based on different levels (Wallace et al., 2001). These levels are then further invoked by Lee et al. as labels, such as *Input interdependency* which addresses unidirectional relationships, *mutual interdependencies* which addresses bidirectional relationships, *shared interdependencies*, as well as *exclusive or (XOR) interdependencies* (Lee et al., 2007).

Four types of connections, including physical, cyber (or information), spatial (or co-located, or geographical, or geospatial), economic (or market, or budgetary), political, are classified based on whether they are functional connections or logical connections. The differentiations of dependence, interdependence and disturbance are further analysed in Table-1 with these five types of connections.

Table-1. Contents of Connection Types

Connection Sources	Contents of Connection Types				
	Functional	Logical	Dependence	Interdependence	Disturbances

			(Unidirectional)	(Bidirectional)	
Physical	Yes	N/A	Yes (e.g. supports from transportation system to emergency response system.)	Yes (e.g. connections between electricity supply system and transportation system.)	Yes (e.g. an unexpecting current because of some broken components.)
Cyber/ Information	Yes	N/A	Few (e.g. government networks using fibre-optic.)	Yes (e.g. communication network based on TCP/IP.)	Yes (e.g. cyber attacks.)
Spatial/ Co-located/ Geographic/ Geospatial	N/A	N/A	N/A	N/A	Yes (e.g. a fire.)
Economic/ Market/ Budgetary	N/A	Yes	N/A	N/A	Yes (e.g. influences from national power market to local power grids.)

Figure-4 shows a new diagram of dependencies according to the entity based model and the categorisations of connections. The "+" sign means that changes of variables pointing to the joint would have contributions to impacts on the changes of variables pointing out of the joint. The "-" sign means that changes of variables pointing to the joint would have impacts that distribute to the changes of variables pointing out of the joint.

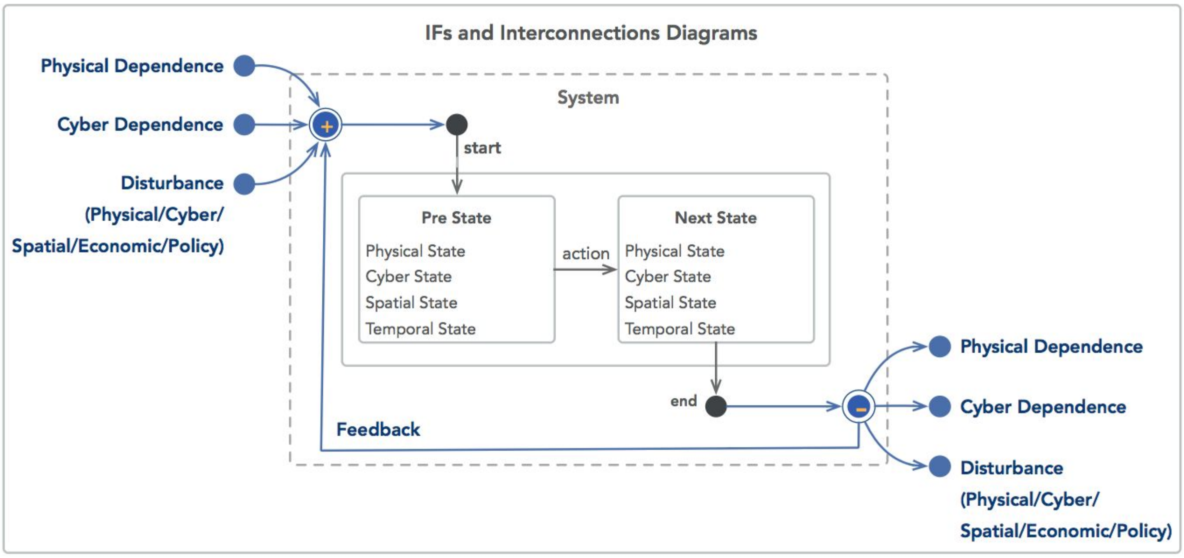

Figure-4. Inter and Intra Connections in CIs

3.3. Dependencies Analysis

Dependencies analysis are carried out through both conceptual and qualitative studies, and also quantitative studies through modelling and simulation approaches.

Qualitative works include governmental reports, organizational management studies, and conceptual analysis. These works focus on definitions, categorisations and strategic research of dependencies in CI, and also highlight the importance of modelling techniques. Quantitative researches could be categorized into mainly six groups, according to the review of Ouyang (Ouyang, 2014). Ouyang divided modelling and simulation approaches into empirical methods, agent based methods, system dynamics based methods, economic theory based methods, network based methods, and others. Empirical methods and economic theory based methods are discussed in more details in logical dependencies section. The other four methods are discussed in the section on dependencies modelling and simulation.

3.4. Logical Dependencies

With technical development contributing to a more interconnected society, the division of the societal responsibilities makes the operation, management and maintenance of CIs societal management more divided. Conflicts have appeared between the increasing interdependence of various technical sectors and the divided responsibilities for managing and operating those sectors, which results in increasing complexities in operation and management of CIs. On one hand, operation of complex functional infrastructure asks for adequate and transparency information to identify overriding risks and vulnerabilities, especially in boundary areas. On the other hand, divided sectors for CIs management affect the functional system in return with barriers in information sharing and unclear responsibility allocation. From repeated experiences, it is clear how these conflicts could influence crisis management of CIs (Hassel and Johansson, 2016).

From the categorisation of connection types in Table-1, it is clearly shown that logical dependencies include economic connections, marketing connections and budgetary connections. Logical dependencies are usually related to human decisions or actions (Min et al., 2007), which makes them even harder to be modified and predicted. Taking the electricity infrastructure as an example, the price of the electricity, the amount of energy production, residential need of energy, and transmission of energy all contribute to logical dependencies of power industries.

The methods that are mainly used in logical dependencies include empirical approaches and economic theory based approaches. The former requires sufficient historical datasets and expert knowledge. Reports and historical recordings are collected for empirical analysis. For example, Luiijf et al. (Luiijf et al., 2008) provided a database of 2517 CIs failures and their cascading failures. To unearth the essence and influencing parameters of logical dependencies, the later approaches that are economic theory based are used. For example, input-output based methods are adopted to show the relationships among critical factors, such as material acquisition, energy production, transmission and distribution to customers (Min et al., 2007). For instance, Santos and Haimes applied demand-reduction input-output model to analyse the demanding and supplying connections among interconnected sectors, including economic sector and transportation-related sectors. They also did case study to show the economic impacts from perturbation propagations. (Santos and Haimes, 2004)

3.5. Interdependencies across CIs

Classifications of CIs normally include eleven infrastructures according to the EU definition (Lindström and Olsson, 2009). Here we only consider the civil ones, and exclude the military ones. These CIs provide support for electricity supply, nuclear industry, water supply, transportation, health, food, information and communication, and also banking and finance. These CIs are highly interconnected and mutually interdependent. Part of their interdependencies are presented in Figure-5.

Some of the infrastructures are dependent upon certain infrastructures, for example, the proper operation of emergency infrastructure relies upon funding support from banking and finance infrastructure, policy support as well as personal support from government infrastructure, water support from water distribution infrastructure especially during fire crisis, food support from food supply system, fuels support from nuclear industry, transportation support from transportation infrastructure to deliver all the needed materials, and communication support from telecommunication infrastructure.

Some of the infrastructures are interdependent. For instance, electricity supply infrastructure provides power support to maintain basic operation of all the other seven CIs. To ensure proper operation of power supply infrastructure, funding support is required from banking and finance infrastructure; policy support is required from government infrastructure; water is needed for cooling from water distribution infrastructure; fuels are needed for running machines from nuclear industry infrastructures; materials shipping is supported by transportation infrastructure; and emergency response from health sector is solicited whenever a failure in the infrastructure occurs and a repair is requested.

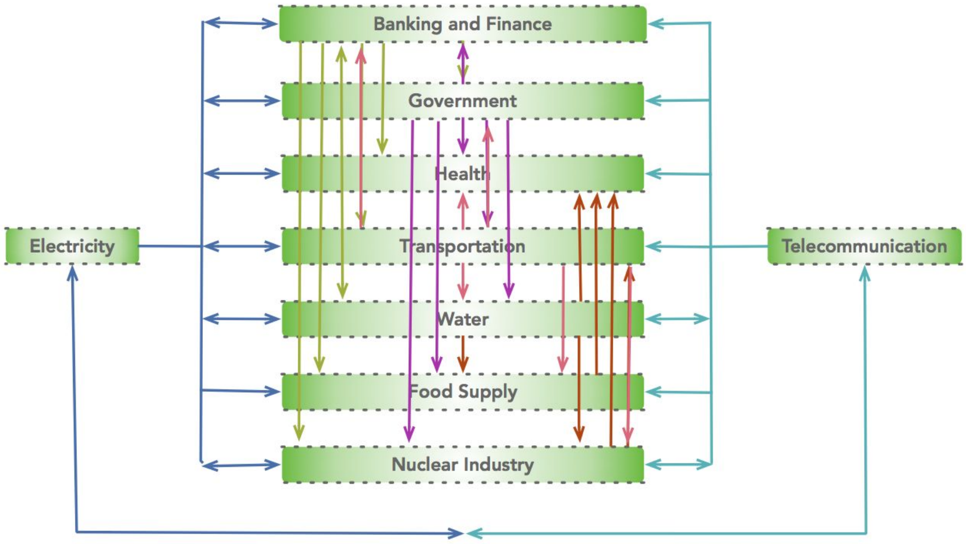

Figure-5. CIs Interdependencies Example

4. Functional Dependency Modelling and Simulation

Functional dependencies are vital to systematic CIP modelling. However, functional dependencies are difficult to be quantified because of their complexity and non-measurability, and therefore deserve more attention. From the categorisation of connection types in Table-1, functional dependencies could come from either physical connections or cyber connections.

4.1. Modelling and Simulation Methods

4.1.1. Meta Modelling

A meta-model is defined as the process of generating, analysing and constructing the concepts and framework as the prerequisite of a model, and therefore called “a model of a model”. It could be used for some predefined problems or to generate computation models for a system development (Klügl and Davidsson, 2013; Assar, 2015). In addition, meta modelling could be used to produce concept definitions and rules of taxonomies.

4.1.2. Automata Based Modelling

Automata based modelling is widely used for events-based system modelling that needs to take into consideration the time factors (Hendriks and Verhoef, 2006). It is also invoked to represent discrete events and control flows.

4.1.3. Network Based Modelling

In graph-based approaches, mathematical graphs are used to represent infrastructure components. To be more specific, the physical topology and configuration of the infrastructures are mapped to graphs which reveal useful information about a system.

- Topological network based approaches: Infrastructure topologies and component taxonomies could be graphed as a web of interacting elements (Yagan et al., 2012).
- Functional network based approaches: These networks include computational modelling and the study of internal flow patterns such as the graph theoretic approach proposed by Svendsen and Wolthusen (Svendsen and Wolthusen, 2007).

4.1.4. Event Based Modelling

- Event Semantics: Lee et al. set up a programming model named programming temporally-integrated distributed embedded systems (PTIDES) that interconnects concurrent software components with discrete events based semantic structures (Lee et al., 2009).
- Event-Condition-Action Model: it only takes into account the scenarios in which the event is produced by a single and homogeneous event source. (MoCarthy and Dayal, 1989)

4.1.5. Agent-Based Modelling and Simulation

A complex system, e.g. smart grids, could be divided into a group of interacting units in the form of software agents. Infrastructures components would be represented as int agents with corresponding rules to define their properties (Klügl and Davidsson, 2013). Agents interacted through feedbacks, both positive and negative following certain power-law distributions. By mapping diverse infrastructure components to different agents, this approach could be used to model heterogeneous complex systems. The limitation of this approach is that the cascading effect modelling and simulation would depend on how the agents are defined.

4.1.6. System Dynamics Based Simulation

System dynamics based methods were developed to embrace the difficulty of hypothesis verification in software engineering. In this approach, the systems are regarded as a whole or a set of “black boxes” with loops and feedbacks. For example, in the works of (Karnopp et al., 2012), graph methods are adopted to show physical system dynamics. Traditionally, the models of separate layers could be constructed invoking different equations or computer simulation schemes from corresponding disciplines. In system dynamics based methods, however, graphs of mixed systems are developed to show the interconnections of this “system-of-systems”.

4.1.7. Probabilistic Risk Analysis Methods

Hernandez et al., proposed a combination modelling of a network graph, an enhanced betweenness centrality for cascading failures approximation, and an interdependence model for coupling uncertainty analysis, to evaluate probabilistic performance. (Hernandez and Dueñas, 2013)

4.2. Methods Classification

Previous research-based analysis could be classified into three main categories, which are holistic approaches, topological based approaches and simulation-based approaches (Setola et al., 2014). Among them, holistic approaches mainly use economic or empirical data to facilitate the models which are infrastructure oriented. Since both economic and empirical data tend to be macro-scale aggregated, such methodologies are not suitable for operative analysis. Topological based approaches refer to the methodologies that make use of the topological structures and complex networks to measure the degree of intra-dependency and interdependency, mainly focusing on functional processes. Topological analyses, however, may not capture the synchronous consequences or influences of the intended services with its static properties. In comparison, simulation-based approaches are more concerned with the persistent changes and dynamic process of the component-based behaviours of the infrastructures, and would be applied in an operational-oriented way. Accordingly, Table-2 shows the categorisation of modelling and simulation methods.

Table-2. Dependence Modelling and Simulation Methods Categories

Models/Simulations	Holistic	Topological-Based	Simulation-Based
Meta Analysis	N/A	Yes	Yes
Automata Based	N/A	Yes	Yes
Network Based	N/A	Yes	Yes
Event Based	N/A	Yes	N/A

System Dynamic Based	N/A	Yes	Yes
Agent Based	N/A	Yes	Yes
Probability Risk Analysis	Yes	N/A	N/A

4.3. Benchmark

In the review of modelling and simulation approaches, (Satumtira and Dueñas-Osorio, 2010) provided evaluation criteria for benchmarks including mathematical methods, objective of modelling, scaling and scoping of analysis, quality and quantity of input data, disciplines being evolved and targeting, end user type. At the same time, taking the essence of dependency/interdependency in CIs into consideration, some requirements of modelling/simulations could be generated. Table-4 shows an example of how some benchmarks are generated and analysed for CIs modelling and simulation.

Table-3. Dependence Modelling and Simulation Requirements

CIs real system characteristics	Modelling and Simulation Requirements
Geographically distributed in the form of large-scale systems while at the same time spatially connected.	Distributed system. Spatial Dependence.
Most systems have physical connections, and also increasing cyber connections for control and operation.	Physical Dependence. Cyber Dependence.
Most systems are influenced by related markets and policy.	Economic Dependence.
Most systems are highly affected by human factors.	Socio-technical system.
Addressed in multidisciplinary fields.	Interoperability. Complexity.
Structures are flexible; connections are flexible.	Adaptivity. Dynamics.
Heterogeneous data are exchanged among inter and intra systems.	Heterogeneous data processing and analysis.
Events are generated and handled based on current situations in real time. Data are transmitted synchronously.	Synchronization. Situation awareness. Time critical.
A trend of invoking more digital techniques.	Autonomation. Emergence.

5. System Integration Method

Interoperability framework is important for model integration and systematic design, and is also a vital part to apply dependencies analysis in CIP. CIP has been a focus of recent literature from the perspective of separate disciplines. For example, improving system stability is a hot topic in electrical engineering and mechanical engineering. Enhancing communication efficiency is vital in information system and technology. Embracing resource management and sustainability is a key in supply chain management to embrace resource management and sustainability. Current research in CIP are faced with new challenges due to the barriers and low interoperability of different fields.

On one hand, different research areas normally have different taxonomies, which results in conceptual confusion when it comes to an interdisciplinary field (Jacobsson T and Jacobsson S, 2014). t is important to understand the principles of CIs as a whole, other than limiting to traditional reductionist methodologies (Albert and Barabási, 2002). A corner-stone in modelling interoperability is to generate an integrated conceptual framework with clear semantics and standardised ontological formations to define CI entities and connections (Tan et al., 2009). The structure of CIs could be extracted as a hierarchical CPS architecture, while the status changing and service maintaining of CIs could be expressed through events and actions.

Here a framework of the testbed of our project is shown. This hybrid framework combined the hierarchical CPS architecture and the invoked event models. CPS architecture contains three layers which are physical platform, embedded rules layer and cyber data layer. These three layers pass on data to the hybrid simulator. All the agents, including process agent, control agent, inventory agent, and cyber agent are connected to hybrid simulator. Hybrid simulator is also connected to the blackboard where the invoked models are generated based on the knowledge database of rules including conditions of interest and the predefined operations following the events. Those events are analysed to generate new rules to be sent out to the scenario player. Then the scenario player would send out new requirements to CPS about which part of data are needed for which agent. The interoperability framework is further shown in Figure-6.

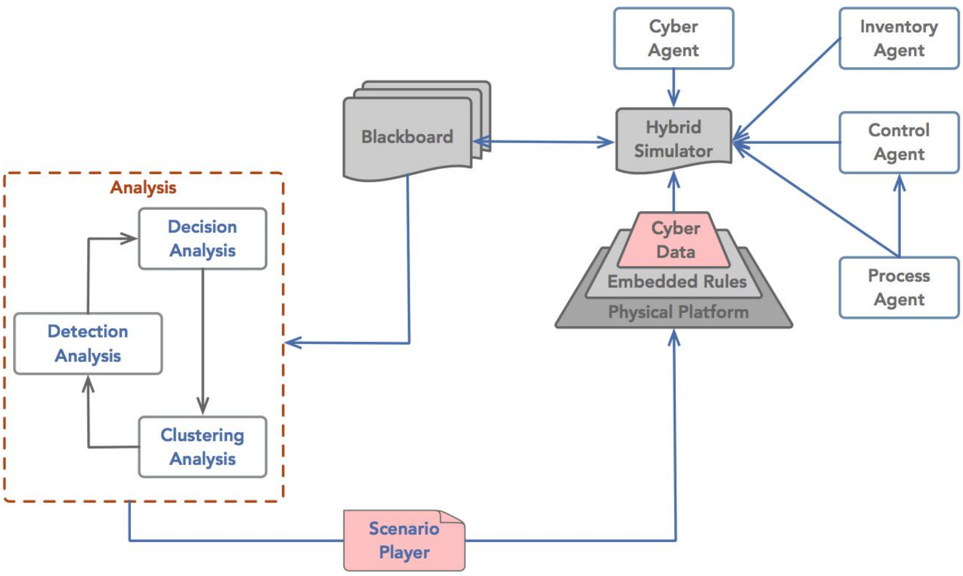

Figure-6. CPS Based Interoperability Framework

6. Conclusion and Future Research

6.1. Conclusion

In the technical report, the connections within and among CIs are explored. Dependencies and interdependencies are defined and discussed, with categorisation of different types of connections like physical connection and cyber connection. The complex dependencies, i.e. logical dependencies and functional dependencies, are discussed in details, with examples and comparisons among related modelling and simulation approaches. In addition, system integration methods are discussed with our own method of multi-agent testbed design. This multi-agent testbed method is briefly explained with a framework.

6.2. Future Research

6.2.1. Dependency Weights and Metrics

Motivated by the importance of understanding the universality and coherence of complex systems, many works have been presented in complex network topologies. Most structures of CI systems could be presented in the form of a graph, using nodes to represent certain entities and edges to show their interactions. Current research on influence weights in the graph of CIs adopt the directed binary networks. Directed binary networks apply specific scaling laws to define the degree of distributions of both the incoming and the outgoing edges, and therefore those edges have fixed weights. However, the incoming edge and outgoing edge in a complex system network should be defined separately and dynamically, which would be part of our future works in the project.

6.2.2. Case Study on Dependence in Power Grids

A case study is expected to be conducted in a contrastive way. More specifically, two dependence frameworks are developed separately following a bottom-up approach from the dispersed heterogeneous engineering perspective, and a top-down approach from the centralized networking and/or controlling perspective. These two frameworks are implemented in modern power-supply CPS monitoring systems and are compared in details.

7. References

Assar, S., 2015, May. Meta-modeling: concepts, tools and applications. In *IEEE RCIS'15: 9th International Conference on Research Challenges in Information Science*.

Albert, R. and Barabási, A.L., 2002. Statistical mechanics of complex networks. *Reviews of modern physics*, *74*(1), p.47.

Carhart, N. and Rosenberg, G., 2016. A framework for characterising infrastructure interdependencies. *International Journal of Complexity in Applied Science and Technology*, *1*(1), pp.35-60.

Crucitti, P., Latora, V. and Marchiori, M., 2004. Model for cascading failures in complex networks. *Physical Review E*, *69*(4), p.045104.

Dudenhoeffer, D.D., Permann, M.R. and Manic, M., 2006, December. CIMS: A framework for infrastructure interdependency modeling and analysis. In *Proceedings of the 38th conference on Winter simulation* (pp. 478-485). Winter Simulation Conference.

Hassel, H. and Johansson, J., 2016. Review of methods for measuring societal resilience and how they address critical infrastructures. In *European Safety and Reliability Conference (ESREL 2016)* (pp. 2090-2097). CRC Press/Balkema.

Hernandez-Fajardo, I. and Dueñas-Osorio, L., 2013. Probabilistic study of cascading failures in complex interdependent lifeline systems. *Reliability Engineering & System Safety*, 111, pp.260-272.

Karnopp, D.C., Margolis, D.L. and Rosenberg, R.C., 2012. *System dynamics: modeling, simulation, and control of mechatronic systems*. John Wiley & Sons.

Klügl, F. and Davidsson, P., 2013, September. AMASON: Abstract meta-model for agent-based simulation. In *German Conference on Multiagent System Technologies* (pp. 101-114). Springer, Berlin, Heidelberg.

Lee II, E.E., Mitchell, J.E. and Wallace, W.A., 2007. Restoration of services in interdependent infrastructure systems: A network flows approach. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *37*(6), pp.1303-1317.

Lee, E.A., Matic, S., Seshia, S.A. and Zou, J., 2009, June. The Case for Timing-Centric Distributed Software Invited Paper. In *Distributed Computing Systems Workshops, 2009. ICDCS Workshops' 09. 29th IEEE International Conference on* (pp. 57-64). IEEE.

Lezama, F., Palominos, J., Rodríguez-González, A.Y., Farinelli, A. and de Cote, E.M., 2017. Agent-Based Microgrid Scheduling: An ICT Perspective. *Mobile Networks and Applications*, pp.1-17.

Lindström, M. and Olsson, S., 2009. The European programme for critical infrastructure protection. In *Crisis Management in the European Union* (pp. 37-59). Springer, Berlin, Heidelberg.

Ljung, L., 1998. System identification. In *Signal analysis and prediction* (pp. 163-173). Birkhäuser, Boston, MA.

Luiijf, H.A.M., Nieuwenhuijs, A.H. and Klaver, M.H.A., 2008, November. Critical infrastructure dependencies 1-0-1. In *Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA), 2008 First International Conference on* (pp. 1-3). IEEE.

Luiijf, E., Nieuwenhuijs, A., Klaver, M., van Eeten, M. and Cruz, E., 2008, October. Empirical findings on critical infrastructure dependencies in Europe. In *International Workshop on Critical Information Infrastructures Security* (pp. 302-310). Springer, Berlin, Heidelberg.

McCarthy, D. and Dayal, U., 1989, June. The architecture of an active database management system. In *ACM Sigmod Record* (Vol. 18, No. 2, pp. 215-224). ACM.

Min, H.S.J., Beyeler, W., Brown, T., Son, Y.J. and Jones, A.T., 2007. Toward modeling and simulation of critical national infrastructure interdependencies. *Iie Transactions*, *39*(1), pp.57-71.

Ouyang, M., 2014. Review on modeling and simulation of interdependent critical infrastructure systems. Reliability engineering & System safety, 121, pp.43-60.

President's Commission on Critical Infrastructure Protection (PCCIP). Critical foundations: protecting America's infrastructures: the report of the President's commission on critical infrastructure protection. Rep. No. 040-000-00699- 1, U.S. Government Printing Office, Washington, D.C.; 1997.

Rinaldi, S.M., Peerenboom, J.P. and Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems,* 21(6), pp.11-25.

Santos, J.R. and Haimes, Y.Y., 2004. Modeling the Demand Reduction Input-Output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures. *Risk analysis*, *24*(6), pp.1437-1451.

Satumtira, G. and Dueñas-Osorio, L., 2010. Synthesis of modeling and simulation methods on critical infrastructure interdependencies research. In *Sustainable and resilient critical infrastructure systems* (pp. 1-51). Springer Berlin Heidelberg.

Setola, R., Lorusso, D. and De Maggio, M.C., 2014, October. Dependencies analysis in emergency scenarios. In *Security Technology (ICCST), 2014 International Carnahan Conference on* (pp. 1-6). IEEE.

Svendsen, N. and Wolthusen, S., 2007, March. Multigraph dependency models for heterogeneous infrastructures. In *International Conference on Critical Infrastructure Protection* (pp. 337-350). Springer, Boston, MA.

Tan, Y., Vuran, M.C. and Goddard, S., 2009, June. Spatio-temporal event model for cyber-physical systems. In *Distributed Computing Systems Workshops, 2009. ICDCS Workshops' 09. 29th IEEE International Conference on* (pp. 44-50). IEEE.

Vespignani, A., 2010. Complex networks: The fragility of interdependency. *Nature, 464(7291),* pp.984-985.

Wallace, W.A., Mendonça, D., Lee, E., Mitchell, J.E. and Chow, J., 2001. Managing disruptions to critical interdependent infrastructures in the context of the 2001 World Trade Center attack. *Impacts of and Human Response to the September 11, 2001 Disasters: What Research Tells Us*.

Watts, D.J. and Strogatz, S.H., 1998. Collective dynamics of ‘small-world’networks. *nature*, *393*(6684), pp.440-442.

Yagan, O., Qian, D., Zhang, J. and Cochran, D., 2012. Optimal allocation of interconnecting links in cyber-physical systems: Interdependence, cascading failures, and robustness. *IEEE Transactions on Parallel and Distributed Systems*, *23*(9), pp.1708-1720.

Zadeh, L.A., 1962. From circuit theory to system theory. *Proceedings of the IRE*, *50*(5), pp.856-865.

Zhang, P. and Peeta, S., 2011. A generalized modeling framework to analyze interdependencies among infrastructure systems. *Transportation Research Part B: Methodological*, *45*(3), pp.553-579.

Zimmerman, R., 2001. Social implications of infrastructure network interactions. *Journal of Urban Technology*, *8*(3), pp.97-119.