Chapter 15

MODELING DEPENDENCIES IN CRITICAL INFRASTRUCTURES

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Abstract This paper describes a model for expressing critical infrastructure dependencies. The model addresses the limitations of existing approaches with respect to clarity of definition, support for quality and the influence of operating states of critical infrastructures and environmental factors.

Keywords: Critical infrastructures, dependencies, modeling, system analysis

1. Introduction

A critical infrastructure (CI) comprises those assets and parts thereof that are essential to maintaining vital societal functions, including the supply chain, health, safety, security and the economy [5]. CI dependencies are important for understanding the cascading effects in the various CI sectors that can have serious societal impact.

However, the models and methodologies available for dependency analysis are very limited. Recent studies of the Dutch national infrastructure [7, 11, 12] have demonstrated the need for a clear, methodical understanding of dependencies. Moreover, real-world dependencies and event data from CI incident databases (e.g., [16]) contain complexities that are not captured by existing dependency models; these complexities are, therefore, often ignored. When important aspects of CI dependencies are not modeled adequately, risk assessments conducted using these dependencies are suspect at best.

This paper describes a model for expressing CI dependencies that is based on a system analysis approach. The model addresses the limitations of existing approaches with respect to clarity of definition, support for quality and the influence of operating states of CIs and environmental factors.

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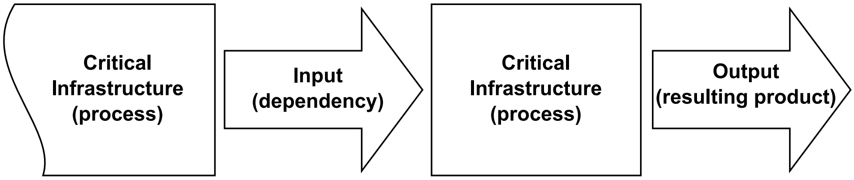

Figure 1. Modeling dependencies.

2. Background

A dependency is a relationship between two products or services in which one product or service is required for generating the other product or service. A product is a tangible or intangible entity created as a result of direct human, machine or system activity. A service is an intangible product. An interdependency is the mutual dependency of products or services [8].

Numerous models have been developed to capture the essential properties of dependencies [4, 9, 10, 14, 15]. Dependencies are classified on the basis of various features, including sector, product (e.g., cyber or physical), coupling (tight or loose), buffered or non-buffered, and policy.

Our experience performing dependency analyses has shown that current methodologies (e.g., [9, 10, 14, 15]) do not provide enough support for modeling the complexities that arise in real-world scenarios. The primary problem is the absence of a clear definition of dependencies. In particular, common cause scenarios are often mistaken for dependencies. In our view, dependencies always deal with the relationships between two infrastructures. Therefore, a vulnerability or threat shared by two infrastructures should neither be included as a type of dependency nor as an aspect of a dependency. Whereas dependencies are the subject of dependency analysis, common cause threats and scenarios are components of risk analysis.

A second problem is the lack of support for modeling essential real-world factors. These include: (i) quality factors other than on/off availability that influence the output of CI products and services, (ii) process states in which the outputs of CI products and services may be produced, and (iii) environmental factors that influence the dependent inputs and processes that output CI products and services.

Our systems approach for modeling CI dependencies was developed to address these shortcomings.

3. Modeling Dependencies

The systems approach views a CI as a process. A CI has one or more dependencies as required input(s) to the process. The approach is equivalent to process modeling, and, in this context, dependencies are modeled as response functions (Figure 1).

In the following, we define the "quality" and "response" elements that describe dependencies, along with the "state of operation" and the "environmental" factors that influence dependencies.

3.1 Quality

Most approaches for modeling dependencies implicitly assume the complete availability or complete non-availability of a CI product or service. However, our experience working on CI incidents around the world [16] and examining CI incidents described in literature (e.g., [13]) has shown that the dependency of a CI product or service is characterized by more than just on/off availability. CI products and services that are input to a CI process also need to adhere to certain levels of quality. These levels of quality may involve various indicators, often specific to a product or service. Key indicators of quality include:

- Quantity/volume (of food, water or power)
- Speed (of transport or information services)
- Reliability (of information)
- Temperature (of heating or cooling water)
- Pressure (of gas or drinking water supply)
- Frequency and voltage (of electrical power)
- Biological and chemical purity (of food, drinking water, surface water or chemicals)

Note that when we refer to input(s) or output(s), all the quality aspects mentioned above are implicitly included.

3.2 Response

A dependency is characterized by the response function that describes the output of a CI as a function of its input(s). The response function depends on the input of products and services and on time.

Input Response. An input response describes the CI output as a function of the CI products and services used as input. Two types of input response are distinguished:

- Functional behavior describing how the CI output and dependency are related when the dependency supply deteriorates.
- Functional behavior describing how the CI output and dependency are related when the dependency supply recovers.

Note that these input response functions can (but need not) be the same. For example, a gas turbine that generates electrical power normally operates with a certain input gas pressure θ. It may operate in a reduced output mode all the way down to a reduced gas pressure of 0.5θ. The gas turbine, however, will not start with a gas pressure less than 0.8θ. In this case, the electrical power output fails (becomes zero) when the gas pressure drops below 0.5θ. When the gas pressure recovers, the power output resumes only after the gas pressure has risen to 0.8θ.

Time Response. A time response describes the output of a CI in terms of its temporal behavior after a partial/complete failure. The time response functional behavior has four aspects:

- The time period between the moment the quality of one or more inputs (dependencies) change(s) and the moment this leads to a (quality) change in the CI output.

- The extent to which the CI output changes as a function of time in response to a change in input quality (or qualities).

- The differential aspect of dependencies. This functional behavior describes the effect on the CI output as a consequence of the speed of a (partial) disruption in a dependency. An example of this effect is the stockpiling of a critical commodity like gasoline after a steep price increase.

- The integrating aspect of dependencies. This functional behavior describes the effect on the CI output as a consequence of the effect that a reduction in the level of satisfaction of dependencies causes a continuously increasing lack of product or service output. For example, a field that receives too little water will yield less and less for each day it is under-watered until the crop eventually dies.

3.3 States of Operation

The state of operation of a CI is one of the main factors that influence a dependency. We define four states of operation:

- **Normal State:** This is the state in which the CI operates under normal conditions.

- **Stressed State:** This is the state in which special measures are required to keep CI operations under control.

- **Crisis State:** This is the state in which CI operations are out of control.

- **Recovery State:** This is the state in which CI operations are under control but have not been restored to normal conditions.

Figure 2 presents the CI state transition diagram. In each state, the set of CI products and services on which the CI output depends and the extent to

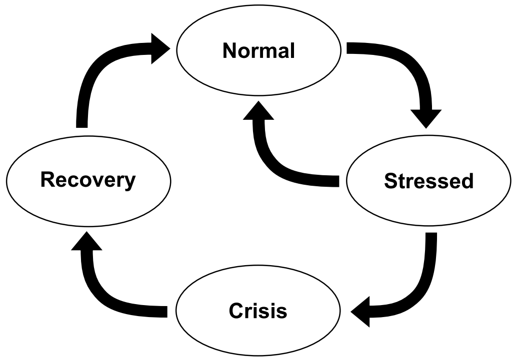

Figure 2. State transition diagram.

which the CI depends on the (input) services and products will, in general, differ. For example, if computer systems are down due to a power outage, there is no longer a critical dependency on telecommunications for the purpose of data transmission. However, if the data can be communicated verbally using a telephone, the critical dependency on telecommunications is increased.

We use hypothetical scenarios in an electrical power grid to clarify the CI states and their transitions. In the power grid, small disturbances occur even in the "normal" state and no special measures have to be taken to ensure control of operations. However, if data communications between the central control room and substations fail, the state of the power grid cannot be monitored and, therefore, the power grid cannot be controlled from the central location. The contingency plan involves dispatching operators to the substations to monitor and control power grid equipment. The operators may use cellular phones to exchange information with the central control room. Because out-of-the-ordinary measures have been put in place to maintain control of operations, the CI is in a "stressed" state.

If the cellular network fails after some time, central monitoring and control of the grid state becomes impossible. The power grid is out of control and is, therefore, in a "crisis" state. After regaining data communications with the substations, the state of the power grid becomes clear at the central control room. However, due to lack of control, the power grid has split into two "islands" and smaller portions of the grid have tripped and, hence, become disconnected from the grid. Note that an island is a power grid partition with specific voltage/frequency characteristics that are different from its neighboring grid(s); this prevents its reconnection with the grid. The operational procedures necessary to recover from this situation are well understood, but they take some time and effort. The power grid is in the "recovery" state until normal operations are restored.

The boundaries between states are often not sharply defined and are open to interpretation. Fortunately, this is not a problem when conducting a dependency analysis, as long as all the states are considered. States can be defined as

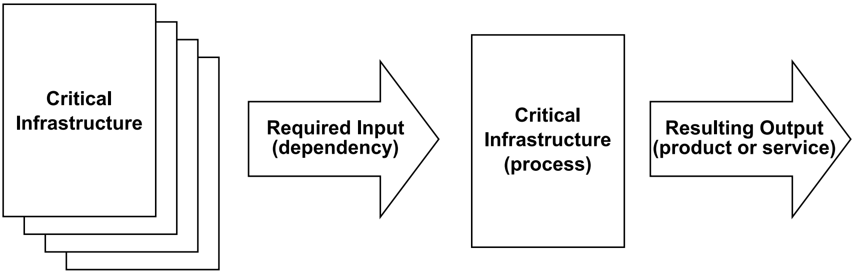

Figure 3. Dependencies as a function of the required output.

needed; it is just that the dependencies that are not considered in one state will be considered as part of some other state. The important issue is to recognize that dependencies can vary according to how states are defined, but all the dependencies in all states of operation must be considered in the analysis.

3.4 Environmental Factors

Certain environmental factors that are outside the scope of a CI can influence dependencies. These factors can worsen or alleviate dependencies, change their response or even create new dependencies. Environmental factors can influence dependencies in the following manner:

- At very low ambient temperatures, the efficiency of a cooling tower increases and a power station may no longer rely on cooling water from a river (input response).
- During rush hour, the effects of a road closure are much more acute than during off-hours (time response).
- In winter, the amount of gas needed for heating is considerably higher than what is needed in summer (quality requirement).

4. Modeling Dependencies

Having identified the elements of CI dependencies, it is necessary to model the relationships between these elements. Note that the reason for constructing a model is not to generate a mathematical description of dependencies, but to formalize the relationships between the elements that have been identified. Therefore, the model is not intended to be used to analyze operational aspects or to conduct simulations.

As mentioned above, a dependency deals with the relationship between a required input for a CI process and the resulting CI process output in the form of products and/or services. This is the domain of process modeling and we employ its terminology and concepts to construct the CI dependency model as shown in Figure 3.

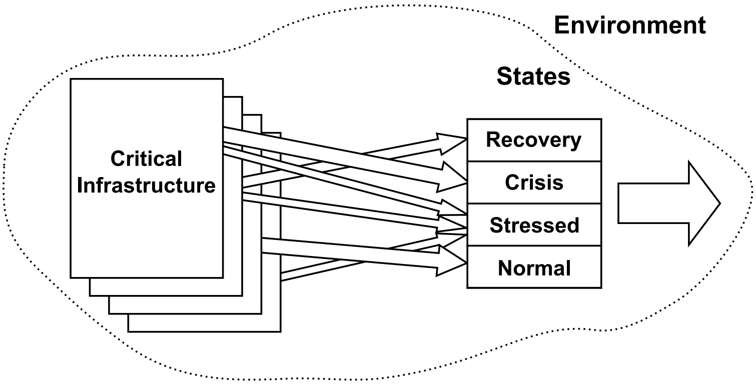

Figure 4. States and environment as part of the dependency model.

The CI output, O, is a function of input and time, i.e., $O = f(I, t)$, where I is the input and t is the time. The time variable describes the time aspects of the inputs, not the changing nature of the dependencies. The dependencies are assumed to be static; their behavior does not change over time.

In general, the CI output is dependent on n inputs and may be expressed as: $O = f(I_{1\ldots n}, t)$. Since each CI input has its own set of qualitative properties, it is represented as a vector of qualitative indicators; thus, the CI output function becomes: $O = f(\bar{I}_{1\ldots n}, t)$. Since the CI output also has a set of qualitative properties, the complete dependency response function can be written as: $\bar{O} = f(\bar{I}_{1\ldots n}, t)$.

The set of dependencies and their qualitative properties are, in general, dependent on the state of the system and environmental factors as shown in Figure 4. Therefore, if a function is defined for every combination of state and environmental factor, the response function of the CI on its dependencies is: $\bar{O} = f_{s,e}(\bar{I}_{1\ldots n}, t)$. This is typically a large set of moderately complex functions that, if developed completely, accurately describes how a CI reacts to changes in its dependencies in all possible situations. Note that the model can also be extended for a CI that produces more than one output by adding a subscript $j = 1..m$ to the output, where m is the number of outputs.

5. Conclusions

The system-analysis-based dependency model provides a classification of the elements and factors that should be considered to completely describe the behavior of CI dependencies. The dependency model also provides a mechanism for communicating dependencies in a concise and unambiguous manner. Our future research will apply this theoretical framework to a well-documented case study [3]. Also, we will investigate the advantages of combining the dependency model with the service-oriented modeling approach used in the EU IRRIIS Project [2].

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