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Modelling Relational Aspects of Critical Infrastructure Systems

Graeme Pye and Matthew Warren
Deakin University, Geelong, Australia
graeeme@deakin.edu.au
mwarren@deakin.edu.au

Abstract: The relational aspects for critical infrastructure systems are not readily quantifiable as there are numerous variability’s and system dynamics that lack uniformity and are difficult to quantify. Notwithstanding this, there is a large body of existing research that is founded in the area of quantitative analysis of critical infrastructure networks, their system relationships and the resilience of these networks. However, the focus of this research is to investigate the aspect of taking a different, more generalised and holistic system perspective approach. This is to suggest that through applying network theory and taking a ‘soft’ system-like modelling approach that this offers an alternative approach to viewing and modelling critical infrastructure system relational aspects that warrants further enquiry.

Keywords: critical infrastructure, dependency relationships, systems modelling

1. Introduction

Modern critical infrastructure systems exist ubiquitously and what constitutes a system evokes different meanings, perceptions and conceptual visualisations to different individuals depending on their interpretation of the focal structure. Essentially, a system construct is a derivation of its functional characteristics, physical structure, response behaviours and incorporates its inferred complexity of components that interact to form a single functional system representation. Systems exist to perform purposeful functions and they are as elementary as a single function system or as a large complex systems comprised of numerous subsystems, all working cooperatively for the common intent (Maani & Cavanaugh 2000).

Systems of this structure are characterised as networks, where the components form the nodes that link together forming the network system topology that facilitate interactions between the nodes within the wider network. Many physical infrastructure systems are characterised as networks, for instance power and water distribution grids are large common examples of networks, but there are many less obvious and smaller example systems cast in this form. The advantage of viewing systems as networks is that their determining behaviour is largely a result of the pattern or topology of network linkages, rather than what specifically passes across the links. Therefore, understanding how the network functions as a degree of its topology can assist in deducing how the system is likely to behave by investigating its network configuration (Finnigan 2005).

There are many different system structures and configurations that characterise network systems and their dynamic functional behaviours. This paper seeks to outline the premise of future research focussing on a particular network theory as the basis of critical infrastructure system research and two interpretative modelling approaches for modelling the relational aspects of dynamic critical infrastructure systems. This will act as a precursor to determining a modelling approach that is suitable for illustrating the inter-system relationships between dynamic critical infrastructure systems and their dependency and interdependency aspects.

2. System dynamics

System dynamics as Forrester (1991, p.5) explains “combines the theory, methods and philosophy needed to analyse the behaviour of systems in not only management, but also in environmental change, politics, economic behaviour, medicine, engineering, and other fields.” System dynamics provides a common foundation that when applied, can deliver insights into changes occurring within systems over time by drawing upon concepts from the field of feedback control.

Therefore, systems dynamics is utilised as a method for analysing, studying and managing complex feedback systems. Feedback is the situation where via a process of ‘cause and effect’, X influences Y, which in turn influences X via a feedback process. Therefore, the study of X and Y cannot be undertaken independently as it is the link between X and Y that predicates how the system will behave (SDS 2006). This example illustrates the circular process where dynamic decisions cause changes that in turn will influence later decisions within the system structure (Forrester 1998) as shown in Figure 1.
The elementary premise of a feedback system is that each action is in response to the current conditions and therefore such actions in turn affect further conditions, which become the conditional basis for future action. There is no beginning or end to this feedback process and this is further complicated with other interconnection relationships and the interactions of human beings (Forrester 1968). As such, the intertwining of many feedback loops can result in local or global cascading chains of actions where a system is reacting to the echo of the system’s past actions, including the past actions of other entwined systems (Forrester 1994 & 1995, Checkland 2000, Watts 2000).

In reality, system feedback is inevitably what confronts people who are responsible for the operational control of dynamic systems in situations such as industrial production, national economics, global warming or even interpersonal relationships. Contextually, the responses to these problems are manifestly dynamic decisions that require additional and related decisions because the situation changes, both by itself and in response to the previous decisions and actions taken (Jensen & Brehmer 2003). As Warren (2005) identifies, the dynamics of systems requires the application of powerful logic to comprehend how systems are consequence reactive to changes and decisions taken in the management and control of such systems, which add further complexity to the operation of dynamic systems.

The study of system dynamics is concerned with constructing quantitative and qualitative models of complex problem domains and then investigating the response behaviours of the system models over time. According to Luna-Reyes and Anderson (2003) system dynamics depends heavily on quantitative data to generate feedback models, although the analysis of qualitative data has a role to play at all levels of the modelling challenge. Often the experimentation undertaken with these models demonstrates how unappreciated causal relationships, dynamic complexity and structural delays become within the subject system, which leads to counter-intuitive results of less informed approaches to improving system functionality. Additionally, system dynamic models enable the incorporation of ‘soft’ factors such as motivation and perception that are advantageous to improved system understanding and management (Caulfield & Maj 2002).

3. Dynamic systems modelling

Constructing a useful interpretation or model a dynamic system requires an analysis of the system to deliver a useful understanding of the system situation through elaboration, exploitation and interpretation of the system. While this is heavily reliant on the mental interpretation of the developer, it is a useful representation of a given understanding of the system situation at a given moment, together with the perceived structure of the system (Schaffernicht 2006). There is no single formalised approach applicable to modelling system dynamics, however Caulfield and Maj (2002) suggest the lessons for modellers are to: just start modelling, try things, listen to the advice of experienced modellers and simply iterate, iterate and iterate the model development process.

Modelling the dynamic behaviours within systems offers some potential benefits including (Caulfield & Maj 2002):

- Dynamic system modelling contributes to developing an understanding of the subject system problem domain through the processes of analysis and critical thinking, as applied to a physical system.

- A primary benefit of dynamic system modelling lies in its ability to not only represent quantitative or ‘hard’ system variables such as program size, staffing numbers or cost of investment; but also the qualitative or ‘soft’ variables that impact system dynamics, such as motivation, commitment, confidence or perceptions.
Traditionally, the focus has been on the quantitative variables of the system because of an applied engineering approach and considerations of the ‘soft’ variables were too difficult to measure and their importance underestimated. Yet the risk of omitting the ‘soft’ variable circumstances is to fail to consider the essential human impact.

System improvement alternatives often come from intuitive insights uncovered during the initial analysis, from the previous experience of the analyst, from proposals forwarded by people operating the system based on their practical experiences and the skill of imagining creative alternatives. As Senge (1990) indicates, the cause of many problems lie in the well intentioned policies designed to alleviate them, developed by policymakers lured into designing and applying interventions that only focus on the symptoms and not the underlying causes. This approach only produces short-term benefits and fosters the need for further symptomatic interventions. However, by modelling and simulating the problem domain using a systems dynamic model, it is possible to enact decisions from a more informed rational basis, safe from the actual physical dangers of real-world experimentation and complexity (Caulfield & Maj 2002).

4. Complex systems paradigm

In essence, the dynamics within each system is dissimilar because of factors such as the structure, environment and complexity of the system itself that will influence the dynamics of systems. The theoretical study of complex systems has been on the organisational arrangements that influence the development and persistence of particular system features. Although it is the relationship between system elements (i.e. structure), rather than the system elements and their properties (i.e. composition) that are significant. The emphasis on structure over composition makes the analytical approach to studying complex systems applicable across disciplines as many different types of systems can be characterised utilising similar analytical tools (Parrott & Kok 2000).

The increased capabilities of computing power have enabled the investigation of networks consisting of millions of nodes and therefore explore questions that were previously beyond comprehension. This according to Christensen and Albert (2007) underlines the need to move beyond reductionist approaches, where understanding of all complex systems is in terms of their simpler components, to an approach that instead attempts to understand the behaviour of the system as a whole.

5. Network systems paradigm

Many physical systems consist of network configurations, for instance, power and water distribution grids are large common examples of networks, but there are many less obvious and smaller example systems cast in this form. The advantage of viewing systems as networks is that typically their determining behaviour is largely a result of the pattern or topology of network linkages, rather than what specifically passes across the links. Therefore, understanding how the network system functions as a degree of its topology can assist in deducing how the system is likely to behave by investigating its network configuration (Finnigan 2005).

Interestingly, the network theory research of Watts (2004) draws together the analysis and modelling of networks incorporating dynamic features of real-world systems, where their interactions are characterised as neither entirely ordered or completely random, but tend to exhibit properties of both. The criterion that is the premise of this network theory is that networks are (Watts 1999a):

- Characterised as a large number of connected elements;
- The network is sparse in structure where each element is connected to only an average but not all other elements of the network;
- The network is decentralised and there is no dominate central point of connection;
- There is a clustering element where there is some degree of overlapping inter-nodal connection between elements within neighbouring network system clusters.

A feature of this type of distributed network structure is that some of the network elements are more significant than others because of their connectedness with other connected elements, including those within other overlapping clusters.

As Callaway et al (2000) attests, the internet, social networks, airline routes and electric power grids exemplify networks of this nature whose function and resilience critically relies on the pattern of interconnection between the elemental components of the system. The degree of robustness or fragility
of the overall system is largely dependent on the configuration of the network connections. Therefore, Callaway et al. (ibid) postulates that if the pattern of connection is appropriately chosen, then the network system can be highly resilient to random lose of network elements resulting in only minimal localised loss of function.

However, the network would remain susceptible to a targeted attack on specifically chosen and significant network elements or linkages, whose loss would globally impact the entire network system functionality. Watt’s (1999b) supports this premise too where the dynamic functional sense of the entire network, local actions within the network system can have causal global consequences. This influence is a product of the relationship between the properties of local and global dynamics that depend critically on the structural connectivity and topology of the network.

Therefore, the anatomy of the network is important because the structure affects the function, so the topology of a social network will affect the spread of information, or disease; likewise the topology of an electrical power grid will affect the robustness and stability of the transmission system and the availability of supply (Strogatz 2001). Many of these network systems exist widely in the modern world and are evident as differing categories of network systems with differing functions, but all serve to link together those elements necessary to achieve the greater goal.

6. Network system types

In achieving their common goal, the nature of networks and their type represent the linkages between differing system entities, which likewise have a vested interest in cooperating together to achieve the greater goal.

There are principally four loose categories of networks (Newman 2003):

1. Social networks consist of a set of people or groups of people with some pattern of contacts or interactions between them.

2. Information networks are sometimes called knowledge networks. The classic example of an information network is the network of citations between academic papers.

3. Technological networks are man-made networks typically designed for the distribution of some commodity or resource, such as electricity or information. The electric power grid is a prime example including the telephone network and the underlying telecommunication infrastructure.

4. Biological networks represent suitable systems in nature and perhaps the classic example of a biological network is the network of metabolic pathways, which is a representation of metabolic substrates and products with connections joining them, if a known metabolic reaction exists that acts on the given substrate and produces a given product.

The common characteristic of these systems is that when a network is carrying a particular resource (friendship, data, electricity or biological substrate) the nodes of the network will experience a load and in normal circumstances the magnitude of the load would not exceed the capacity of the node.

Unfortunately failures tend to cascade in a network environment, for instance, if a heavily loaded node is lost, then a redistribution of the load (i.e. the flow passing through it) to other functional nodes within the network is undertaken. However, this redistribution may cause other nodes to exceed their load capacity causing them to fail too, thereby propagating the failure to the extent that it cascades across the network until all network nodes fail. Although, if the overloaded node did not fail, then protection mechanisms shut it down anyway, to prevent a node failure from propagating throughout the network and cascading across the entire network (Newth & Ash 2005). Normally network systems can cope with load changes and adapt in a limited manner to address those problems of load distribution, although they are not strictly adaptive or necessarily totally autonomous systems.

For example, large-scale interconnected infrastructures such as telecommunications networks and the internet are complex adaptive systems. These infrastructures are vastly more adaptive and dynamic in comparison to their predecessors and consist of large numbers of diverse components and participants of differing forms, function and capability (Herder & Verwater-Lukszlo 2006). Additionally, these infrastructure systems also exhibit characteristic unstable coherence and resilience in spite of
environmental disruptions or central governance (North et al. 2002) and go a long way towards being resilient systems.

Furthermore from the networked system perspective, the research of Watts (2004) draws together the analysis and modelling of networks incorporating dynamic features of physical systems, where their interactions are characterised as neither entirely ordered or completely random, but tend to exhibit properties of both. The premise of this network structure criteria is that networks are: characterised as a large number of connected elements; the network is sparse in structure where each element is connected to only an average but not all other elements of the network; the network is decentralised and there is no dominate central point of connection and finally the network is clustered where there is some degree of overlapping connection between elements within neighbouring system networks clusters (Watts 1999a). The significance of this view of critical infrastructure systems is that it characterises to an extent the structure of these systems and their inter-connections. This then forms the basis for further research to apply this to the topology of network systems and to model the relational and influential aspects of critical infrastructure interconnection.

7. Modelling system relationships

The primary intention of system modelling is to utilise conceptual modelling as a means of facilitating the comprehension of patterns of change, functionality and dynamic behaviours that a system exhibits and to identify the conditions that cause systems to remain stable or become unstable. Furthermore, through experimentation applied to system model parameters and characteristics, the knowledge derived can suggestively indicate what may or may not translate into the real-world system situation. However, it is important to be mindful that the interpretation process of translating physical systems and information into various model elements requires persistence and remains an inexact process, but applied trial and error and experiential judgement remain valid approaches to model development (Stacey 1996).

7.1 System dynamics, the causal modelling approach

In this example a small business system process illustrates the dynamic characteristics of a simple business situation in relational terms, utilising a causal loop diagram to represent the dynamics of the system process. The example models a simple advertising premise for the sale of a durable product and the initial assumption is that there is a pool of Potential Customers who may become Actual Customers through product sales. As Figure 2 depicts, Potential Customers and sales as connected via a negative feedback loop with the goal of reducing Potential Customers to zero. However, after an advertising campaign it is reasonable to assume that the greater number of Potential Customers, the greater number of sales generated, thus indicated by the positive (+) arrow between Potential Customers and sales. Similarly, greater sales reduces the number of Potential Customers (as they are converted to Actual Customers by sales) and this is shown by the negative (-) arrow from sales to Potential Customers. In this case the causal loop diagram in Figure 2 is a negative feedback loop because of the odd number of negative links in the feedback loop between Potential Customers and sales (Kirkwood 2005a).

![Causal Loop Diagram](image)

**Figure 2:** Advertising example causal loop diagram (Kirkwood 2005a)

The conclusion drawn from the diagram modelling this dynamic process is the obvious insight that the number of sales will reduce to zero when the number of Potential Customers reaches zero. This simply illustrates how a causal loop diagram can model a dynamic system process, however the insight gained here would not be particularly useful, as there is no information regarding the rate at which the number of Potential Customers would diminish in this case (Kirkwood 2005a).

The causal loop approach is particularly useful for representing the dynamic and changeable nature of system and process relationships that are typically difficult to describe verbally, because normal language presents interrelations in linear cause and effect chains, while Figure 2 shows that in the actual system
there are circular chains of cause and effect \( \textit{ibid} \). Furthermore, the modelling of dynamic systems incorporating greater system complexity and interaction together with additional system component relationships is possible with causal loop diagrams, and the following example illustrates this further and explains the notation used.

### 7.2 Causal loop diagram notations

The causal loop diagram in Figure 3 is a conceptual model representation of the systematic process of filling a glass of water. This diagram includes elements and arrows (the causal links) linking the various elements together and includes either a positive (+) or negative (-) sign on each link to indicate the following intentions (Kirkwood 2005b):

- A causal link from one element A to another B is positive (+), if either A adds to B or a change in A produces a change in B in the same direction.
- A causal link from one element A to another B is negative (-), if either A subtracts from B or a change in A produces a change in B in the opposite direction.

The model representing the filling a glass of water example utilises the modelling notation as illustrated in Figure 3.

**Figure 3:** Causal loop diagram notations (Kirkwood 2005b)

Initially to describe the model, if the Faucet Position is increased then the Water Flow increases and therefore the causal link (arrow) is positive. Similarly, when the Water Flow increases then the Water Level in the glass will increase and therefore the causal link between these two elements is positive (+) too. The next element is the Gap and this signifies the difference between the Desired Water Level element and the actual Water Level (i.e. Gap equals Desired Water Level minus actual Water Level). From this it follows that an increase in Water Level decreases the Gap and this is a negative (-) causal link. Finally, to complete the causal link back to the Faucet Position, a greater value for the Gap logically leads to an increase in Faucet Position, which is a positive (+) causal link. Although remembering that the additional causal link shown in the diagram from the Desired Water Level to the Gap element is modelling an existing external influence to the system process and from the explanation given above, the influence is in the same direction along this causal link and is therefore a positive (+) causal link (Kirkwood 2005b).

The sign of a particular loop referring to the whole feedback system process is determined by counting the number of minus (-) signs on all the causal links making up the entire loop. More specifically:

- A feedback loop is positive and denotes a plus (+) sign in parentheses, if the loop contains an even number of negative causal links.
A feedback loop is negative and denotes a minus (-) sign in parentheses, if the loop contains an odd number of negative causal links.

In the Figure 3 example, the diagram represents a single causal feedback loop with one negative sign on its causal links only and hence an odd number of negative signs. Therefore, in the centre of the loop diagram the negative (-) sign in parentheses consists of a small looping arrow to indicate clearly that the sign is referring to the whole loop (Kirkwood 2005b).

The causal loop diagram modelling approach may prove applicable for modelling the inter-relationships between critical infrastructure systems and warrants further investigation. However, this requires further research and application in the context of modelling critical infrastructure system relationships to judge its effectiveness.

7.3 Stock and flow modelling approach

Another form of dynamic system modelling that is growing in popularity within business particularly is the stock and flow diagram whose notation consists of three different types of elements, namely, stocks, flows and information. The three elements together in a diagram graphically represent any dynamic process that may be apparent in any business and therefore can be utilised to represent the characteristics of such processes and illustrate the relationship among variables that have the potential to change over time (Kirkwood 2005a).

Figure 4 illustrates an example of a very simple stock and flow diagram with the three elements Casual Staff, sales and Permanent Staff which models the structure of the business process concerning the rate at which Casual Staff numbers reduce to zero, as the number of Permanent Staff required is dictated by the flow of sales.

![Stock and Flow Diagram]

**Figure 4**: Example stock and flow diagram (Kirkwood 2005c)

The two different types of variables illustrated inside the rectangles are called a stock, level or accumulation. The variable sales is shown next to the ‘butterfly valve’ or ‘bow tie’ symbol and this type of variable is known as a flow or rate, thus the two lines through the butterfly valve look like a pipe with the valve controlling the flow. The premise of the above figure is that it represents the flow of Casual Staff towards Permanent Staff, with the rate of flow controlled by the sales valve; this is the key idea behind the difference between stock and flow. Therefore, a stock represents an accumulation of something and a flow is the movement of something from one stock to another (Kirkwood 2005c).

The final element of Figure 4 is the information link represented as a curved arrow and this notation represents the value of Casual Staff influencing the value of sales. Additionally, and of equal importance, is the lack of an information arrow from Permanent Staff to sales, which illustrates that information regarding the value of Permanent Staff has no influence over the value of sales (*ibid*).

7.4 Stock and flow appraisal

The purpose of the stock and flow diagram is to depict the process changes and how the elements and the structure of these processes interact together to bring about change. This form of modelling focuses on the elements that make up the process (sometimes likened to the components of the system), and how the performance of the process changes over time and forms the basis of studying the dynamics of a simple process using stock and flow diagrams.

The underlying weakness of stock and flow diagrams is that they can only deliver a simplistic representation within a defined process boundary of a simple process. Unfortunately, from the
perspective of modelling examples of critical infrastructure systems for instance, stock and flow diagrams are not readily applicable to this type of system modelling due to the size and complexity of the systems. The other important issue is the scalability potential of stock and flow diagrams with regard to these systems as they tend to become difficult to interpret due to the diagrams added complexity in depicting the logical interconnection, processes and dependency relationships of critical infrastructure systems. It appears that stock and flow diagrams are better suited to modelling less complex system processes with clearly defined boundaries, and is not necessarily well suited to modelling multiple interconnected and large complex critical infrastructure systems from a relational perspective.

8. Conclusions

As Bentley (2006) intimates, critical infrastructure systems tend to be interdependent and even interconnected, and system failures – be it through natural disaster, terrorism or poor management – can bring entire communities and their industries and utilities to a grinding halt. Therefore, the ability to analyse and critique the relational aspects of critical infrastructure systems, together with modelling these system relationships offers an avenue for assessing critical infrastructure system security, identifying vulnerabilities and locating inherent weaknesses to system availability and service supply.

The research of Watts (1999b) and its interpretation of the interconnections between systems and the structure of social networks, presents an interesting approach that could provide insight when applied to critical infrastructure systems. Although this is not applied here, it represents an opportunity for future research in this area, particularly in terms of identifying the integral interconnections between systems.

Additionally, this offers the opportunity through the identification of these integral interconnections between critical infrastructure systems to utilise the Causal Modelling approach to interpret the influential aspects of relationships between critical infrastructure systems. Causal Loop diagrams offer a flexible 'soft' approach to enable an illustrative representation of critical infrastructure system dependency and interdependency relationships that is worthy of future research.

References

Graeme Pye and Matthew Warren