Investigating dependencies between railway systems and other infrastructure systems: using a scenario-based case study approach

By

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Thesis declaration form

I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Infrastructure systems are developed in a highly interdependent and interconnected way at multiple levels. There is a need to consider infrastructure interdependencies for adaptation in the event of future challenges (e.g. climate change) as well as for proactive risk management strategies and other future decision makings. However, academic literature reveals a gap of knowledge about some dependencies that exist between technical infrastructure systems.

Railways, as complex systems, have a large number of dependencies. In this thesis the interdependencies between the different railway sub-systems and other infrastructure systems have been studied. The existing literature in this subject has been thoroughly reviewed and it has been found that the dependencies at a sector level and a technical environment have not received enough attention and that there are many poorly understood dependencies.

In this thesis two scenarios of dependencies related to railways have been investigated. The first scenario concerns the dependency that exists between electricity generation (power output) and freight railway traffic and was investigated using data related to sectors and time-series analysis. The second investigation was carried out to evaluate the dependency that exists between railways and urban water distribution systems in the event of track flooding caused by a water main burst. As a part of these analyses, a novel modelling and simulation technique has been developed. Hydraulic and numerical simulations have been used to quantify the dependencies which have been highlighted qualitatively by stakeholders and experts. Unlike in the previous research in this field, for which usually the availability of the simulation tool dictates the interdependency analysis, the model and simulation techniques used for this work have been developed based on the requirement of the dependency scenarios.

It is concluded that, by adapting a participatory modelling approach, scenario-based case studies can provide valuable insight into poorly understood infrastructure dependencies.

Impact statement

This thesis provides a comprehensive and critical review of the existing knowledge as well as of the commonly used methods and models in the field of infrastructure dependencies. The review can provide a useful basis for future academic references in the fields of security of critical infrastructure systems, reliability engineering and system safety, policy and decision making, etc.

This research used a combination of stakeholder engagement, scenario analysis, case study and numerical simulation in a bottom-up approach to investigate poorly understood dependencies between technical infrastructures such as railways and water distribution networks. Therefore, this study presents a different application of a combination of well understood methods as the overall approach of the research. A similar approach can be adopted by academic and industrial researchers to study other dependencies across sectors for purposes such as proactive risk management and developing decision making tools (e.g. for future and long-term investments).

The phases of defining the research question and data collection of this research included numerous meetings, interviews and workshops with a significant number of industrial stakeholders from rail, power, road, environment and supply chain sectors. The research provided a mechanism which facilitated communication as well as data and information sharing between practitioners of different technical sectors regarding cross-sectoral risks. A number of these communications resulted in the creation of new projects and activities among these sectors.

Moreover, the ultimate benefit of this research is the creation of a tool that supports the improvement of the resilience of the railway systems to risks that may initiate outside the traditional boundaries of the railways.

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Chapter 1 Introduction

The railways as complex systems have many dependencies. Assets, resources and materials within the system are dependent on other assets, resources, materials or conditions inside and outside of the railway system. For instance, the operation of communication and signalling assets depends on the National Grid system in terms of the receipt of electrical power. Communications can be delivered only if the relevant people, material, machinery and fuel coexist under the right conditions. The dependencies need to be considered for normal operation as well as risk conditions for technical infrastructures such as railways. Disturbances can travel across or through dependent infrastructures and return to the infrastructure where the disturbances initiated. Indeed, cascading failures normally reveal the inherent interdependencies of technical infrastructures at interfaces. One clear example of such cascades was witnessed in the Baltimore freight train crash in July 2001, which occurred in a freight through-route tunnel under Howard Street in Baltimore, Maryland, USA. In addition to the predictable impacts on the railway and road traffic, including delays in coal and limestone delivery, the accident damaged the water system assets and caused localised flooding, which knocked out the electricity supply in the area and led to disruptions of phone, mobile phone and internet services (Pederson et al., 2006).

The present chapter introduces several fundamental concepts and definitions for better understanding of the subject under investigation. The nature of the complexity and interdependency of the national infrastructure systems, the current and future challenges regarding infrastructure systems as well as the role of railways as a sector of transportation in infrastructure systems is described. The motivation, aim and objectives of this research are highlighted and the overall structure of the thesis is explained.

1.1 Background

This section includes a summary of definitions related to infrastructure systems, their complexity and interdependencies.

1.1.1 Infrastructure systems

The term infrastructure is defined as "the basic physical and organizational structures and facilities needed for the operation of a society or enterprise" (Oxford Dictionaries, 2018). In the academic literature, Brown et al. (2004) explain that "infrastructures are a complex set of interconnected, interdependent, adaptive systems on which the nation, manufacturing systems and individuals depend". Rinaldi et al. (2001) refer to infrastructure as a network of publicly and privately-owned man-made systems and processes that collaboratively function. Additionally, Pederson et al. (2006) mention that health, wealth, and security of nations rely on the production and distribution of certain goods and services provided by national infrastructures. Examples of infrastructures include energy, communications, Information Technology (IT), transportation, water, waste, commercial facilities, financial services, government facilities, defence, space, food and agriculture, healthcare and emergency services.

Not all national infrastructures of a country are critical infrastructures that in fact constitute the daily life support systems for nations. The definition of critical infrastructures varies slightly depending on the scale (e.g. regional, national and international) at which these infrastructures are assessed. However, generally critical infrastructures are known as the backbone of the society which provide life-essential services such as: shelter, food, water, sanitation, evacuation and transportation, power and fuels, medical care, public safety, communication and access to financial resources (Johansson, 2010). The United Nations (2018) stated that, worldwide, citizens expect and rely upon critical infrastructures for their health, safety, security, wellbeing and economy. In the United States, a report of the President's Commission on Critical Infrastructure Protection defined critical infrastructures as those whose inadequacy would have a weakening effect on defence and economic security (PCCIP, 1997). In the UK, National Infrastructures are defined as "those facilities, systems, sites, information, people, networks and processes necessary for a country to function and upon which daily life depends. It also includes some functions, sites and organisations which are not critical to the maintenance of essential services, but which need protection due to the potential danger to the public" (civil nuclear and chemical sites for example) (CPNI, 2018). Similarly, in Australia, critical infrastructures "are those physical facilities, supply chains, information technologies and communication networks, which if destroyed, degraded or rendered unavailable for an extended period, would significantly impact on the social or economic wellbeing of the nation, or affect Australia's ability to conduct national defence and ensure national security" (TISN, 2018). From a European perspective, "critical infrastructures are those which are of the highest importance for the community and which if disrupted or destroyed would affect two or more member states/countries". This includes cross-boundary effects as a consequence of interdependencies (or links) between interconnected infrastructures (EN, 2006).

The list of critical infrastructures presented by different nations or bodies are usually consistent (both in academic literature and official governmental reports) and include the following examples: energy systems, digital communications and information systems, transportation systems, water supply and wastewater systems, solid waste systems, vital human services (e.g. health and emergency) and banking and finances (PCCIP, 1997, Rinaldi et al., 2001, EN, 2006, CPNI, 2018, Homeland Security, 2018, TISN, 2018 and United Nations, 2018).

Within the above-mentioned list, the "critical technical infrastructures" are those which are often described in the academic literature as "large-scale, spatially distributed systems with high degrees of complexity" (e.g. power, transportation and digital communications and information systems) (Johansson and Hassel, 2010). The current thesis focuses only on critical technical infrastructure systems (i.e. excludes banking, health etc.) and therefore, where infrastructures or infrastructure systems are mentioned, the technical ones, including primarily energy, information and communications/ICT, transportation, waste and water systems, should be considered.

1.1.2 Technical infrastructure systems

In the academic literature technical infrastructures are defined as systems which serve large spatial scales such as a country or city. Technical/physical infrastructures including transportation and power usually consist of several sectors. For example, transport which provides services moving people and goods can be split into air, rail, road and water. The diverse attributes of the energy, transport and water technical infrastructure systems in the UK can be summarised as in Table 1 (Larsson and EK, 2004, Johansson, 2010, Johansson and Hassel, 2010 and Hall et al., 2012). For the purpose of limiting the scope of this work, the other technical infrastructures (namely ICT and waste) have not been considered and information regarding other systems can be found in Hall et al. (2012) and other similar sources. Furthermore, understanding the interaction of components as well as the overall operation of technical infrastructure systems needs technical understanding of the fields of applied and industrial science (Johansson, 2010).

Table 1 Characteristics of the UK energy, transport and water infrastructure systems (extracted from Hall et al., 2012)

	Energy	Transport	Water
Sectors or sub-systems	• Electricity • Natural gas • Liquid and solid fuels	• Road • Rail • Aviation • Shipping	• Water supply • Wastewater treatment • Sewerage
Scale of governance	National and international	Regional, national and international	Regional
Ownership	Private	Mixed by mode	Mixed by region
Governance and regulation	Varies, e.g. electricity has unregulated market prices but regulated network charges (Ofgem)	Varies, e.g. rail has regulated efficiency targets and prices; roads are government planned with some private provision	For England and Wales, price and investment regulated by Ofwat, drinking water quality regulation by DWI, Environmental regulation by EA. Similar structure in Scotland
Challenges and issues	• Security of supply • GHG emissions targets	• Road congestion • High speed rail • Airport capacity	• Demand management • Climate change • Environmental regulation • Energy costs

1.1.2.1 Energy/power systems

Affordable and green energy is essential for economic prosperity and social development. Almost all goods and services have impacts on energy consumption: agriculture and food, buildings including homes and offices, transport including rail and road, water treatment and supply, manufacturing etc. Globally, energy makes a large contribution to national economies. In the UK "for 2017, the contribution by the energy infrastructures/industries in total to the UK economy was 2.9% of the GDP (0.1

percentage points higher than in the previous year)". Of this figure, "oil and gas extraction accounted for 29%, electricity accounted for 42% and gas accounted for 17%" (National Statistics, 2018). In 2012, primary energy consumption increased by 2.1% from the previous year, owing to the average annual weather temperature being 1 degree Centigrade cooler and also consumption increase in domestic (11%) and services (2.7%) sectors. The UK government's projections showed that the industrial sector will have a larger share of the electricity demand by 2020, with a corresponding lower share in the residential sector (Baruah et al., 2016).

While liquid fuels play the major part in transportation, solid fuels (e.g. coal and biomass) are mainly used as an input for electricity generation. Moreover, both liquid and solid fuel networks transport energy over long distances (Baruah, et al., 2016). In the UK, the main energy networks are the gas and electricity systems. While gas is used to heat homes and provide energy to businesses and to generate electricity, an electrical power network includes the generation, distribution, transmission and utilization of electric power and electrical devices connected to the system including generators and transformers (VELCO, 2018). Gas and electricity systems can be both sub-divided into the following systems: "fuel source (coal, gas oil, uranium, etc.) and power generation (for electricity); transmission (high voltage power network; high pressure gas network); distribution network (medium/low voltage power network; medium/low pressure gas network) and consumers/customers" (electricity/gas demand) (Baruah et al., 2016). Figure 1 shows a basic structure of a typical power (electrical) system as an example. Note that regarding the difference between transmission and distribution, transmission networks transports electricity over long distances at high voltages. Distribution networks operate at lower voltages and take electricity from the transmission system to customers (Energy UK, 2018).

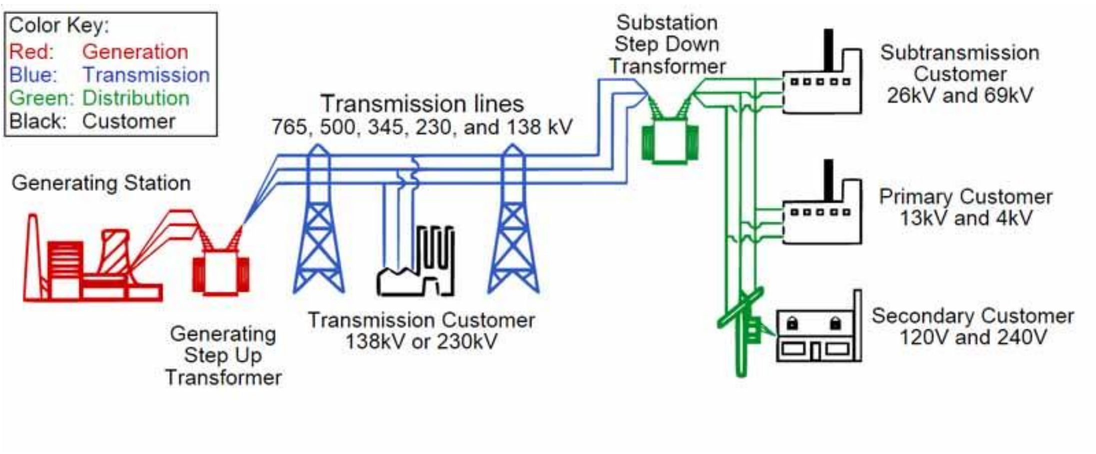


Figure 1 A basic structure of a typical electrical power grid/system (source: VELCO, 2018)

For the gas system, the U.K. has nine gas terminals. The largest two are the St Fergus (indigenous and Norwegian gas supplies) and Bacton (indigenous and Belgian/Continental gas supplies) gas terminals. The U.K. was self-sufficient in gas supplies, but by 2005 most of gas is imported (Baruah et al., 2016).

There are important differences between gas and electricity systems. Natural gas is a primary form of energy which is found in gas fields, while electrical energy is a secondary form of energy which is generated from the transformation of primary energy (usually solid fuels) in power plants. Usually pipelines transport electricity from the gas fields to customers while power circuits transmits electricity to homes and businesses. Additionally, excess natural gas can be stored to be used at peak load periods while electricity cannot yet be stored very efficiently (Tran et al., 2018). The electricity transmission network transports electricity from power plants to distribution companies and large industrial consumers. The distribution companies carry the electricity to other customers through lower voltage networks (Baruah et al., 2016).

In the UK electricity and gas companies are privatised and energy companies can contribute to any of the sub-systems (broadly; generation, transmission and distribution and supply), while some operate in all of them. Most electricity is produced at large electricity power plants which are connected to the national transmission network. Nevertheless, electricity can also be produced in smaller power stations which are connected to the regional distribution networks. Market signals and government policy on issues such as the environment largely influence the decisions of companies regarding the number and type of power station they build. The companies in the electricity generation sector vary from large multinationals to small, family-owned businesses. The transmission system is operated by the National Grid, which is accountable for balancing the system and ensuring that the supply of electricity meets the demand. A similar arrangement exists for the transmission and distribution of gas. Suppliers purchase energy in the wholesale market and sell it on to customers in a competitive market (Energy UK, 2018).

1.1.2.2 Transport systems

An essential component of human societies is the movement of people, goods and information which is provided through a network of options known as transportation infrastructure systems. The systems include the sectors of air-based transport and land-based transport, which consist of road and rail and water-based transport. The transport systems facilitate connection and mobility required for businesses, services and supply chains. Additionally, transport systems improve accessibility of vital resources for daily activities and in emergency situations. A transport system consist of fixed facilities (e.g. roadway and railway), the flow entities (e.g. people, cars, trains), and control systems (e.g. signalling) that permit people and goods to move efficiently and timely to participate in some desired activity (Faturechi and Hooks, 2014 and Rao, 2015).

Based on investigations carried out for HM Treasury, it is evident that a comprehensive and highly effective transport system acts as a vital enabler of sustained prosperity for the UK. It is also stated that transport is an enabler that can improve productivity when other settings are right but cannot independently create economic prosperity. Main linkages by which transport improvements have had an impact on economic growth include improved business efficiency, the increase of domestic and international trade and the attraction of globally mobile activity (House of Commons, 2011).

In 2017, the length of the roads in Britain was estimated to be 396,700 km, with a total of 526 billion vehicle kilometres travelled on these roads. The British railway system carried 64.7 billion passenger kilometres in 2017/2018 on a network covering 15811 route kilometres, with the former figure almost certainly at its highest ever level, alongside 17 billion freight net tonne kilometres (Hall et al., 2016, Dft, 2018a, DfT, 2018b). Ports are also essential to the UK economy, with around 95% of all imports and exports being transported by sea. British seaports handled 481 million tonnes passing through all UK ports in 2017 (remaining level compared to 2016) (ORR, 2018), while British airports were used by 220.6 million terminal passengers, a figure which is still 7% down on the peak in 2007 (Hall et al., 2016). Figure 2 shows the transport statistics for Great Britain in 2018 by modal comparisons of passenger transport and Figure 3 shows the domestic freight statistics in Great Britain.

Transport is now the largest contributor to GHG emissions in the UK after recognizable reduction of emissions from the energy sector (DfT, 2018b). The greatest proportion of the total carbon emissions from transport in Britain (including both domestic and international transport) is generated by cars and taxis (40.3%), with road traffic in total responsible for 67.5% of transport emissions. However, the next biggest contribution is made by air transport, with international and domestic aviation together responsible for 21.6% of transport emissions, a proportion that has increased from 11% in 1990 (Hall et al., 2016).

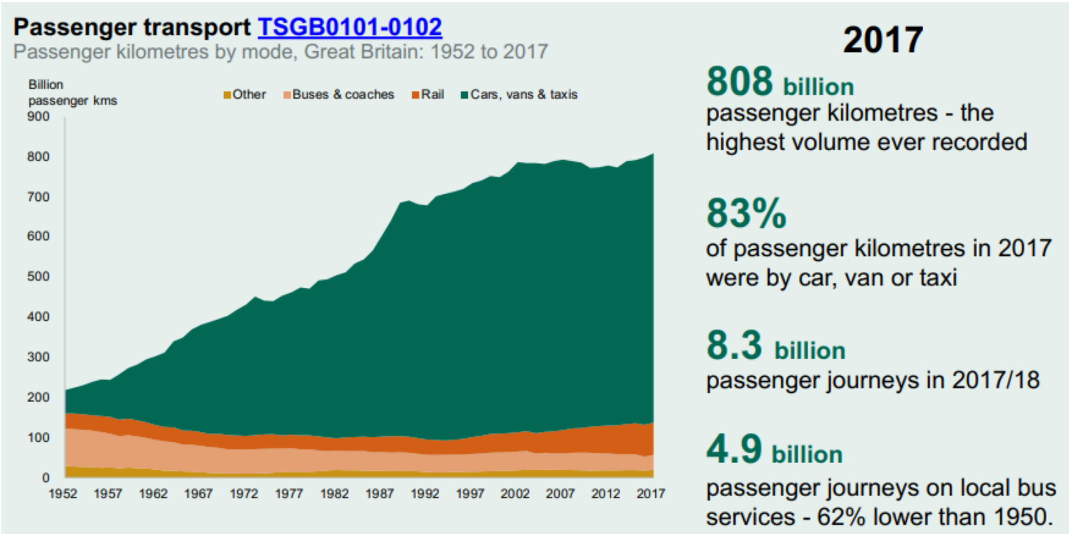


Figure 2 Transport Statistics Great Britain 2018 by Modal Comparisons and passenger transport (source: DfT, 2018b)

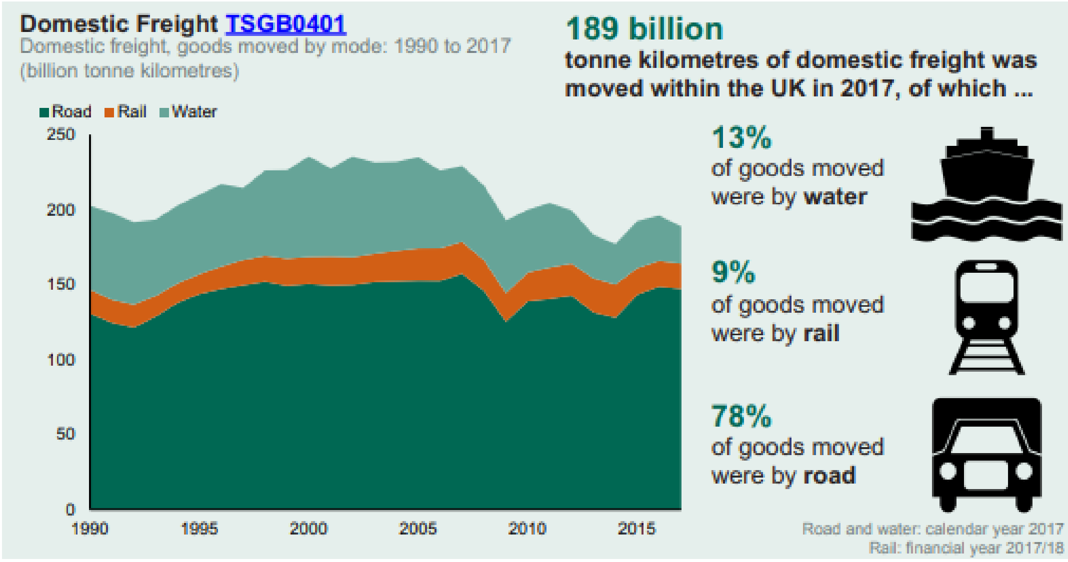


Figure 3 Domestic freight statistics in Great Britain (source: DfT, 2018b)

1.1.2.3 Water systems

Improved drinking water supplies now reach 89% of the world's population, with an increase of 2.3 billion people since 1990, however, in a developed world, the provision of drinking water should be universal (World Health Organisation and UNICEF, 2014). The water resource system for England and Wales provides around 13.7 billion cubic metres of water per year. Much of this is from surface water, which accounts for 85% of the provision in England and Wales. Demand for water can be classified into domestic and non-domestic uses. Industry, power generation, primary production and commerce are the non-domestic users of water. In addition to the demands for water by domestic and non-domestic users, water is also used in the processes of treatment and distribution by water companies (Simpson et al., 2016).

In general, water infrastructure can be categorised into raw water, treated water (including treatment and distribution sub-systems) and wastewater sectors. The raw water sector extracts/collects, transports and stores water before treatment. Usually, raw water is obtained from a lake or reservoir, directly from a river or from groundwater. The treated water sector starts with the treatment works and distributes water in pipes from the treatment works to the various consumers of water through local treated water storage units (Simpson et al., 2016). The water treatment process varies based on the quality and the source of the water, but it usually goes through a set of specific processes before being pumped into the network of homes and businesses. Typically, after the abstraction of raw water the processes at water treatment works consist of storing at reservoir, screening, clarification, filtration, aeration, Granular Activated Carbon (GAC), ozone dosing, disinfection and ammoniation (Thames Water, 2016). Following treatment works (where available)a system of pipes, channels and vessels (known as a distribution system or distribution network) store and convey water to consumers. A distribution network is formed of one or more pipes, often with one or more connected reservoirs and/or tanks, and chambers, and is built from a variety of materials and water fittings (plumbing products). Valves of various types, hydrants, pumps, connection facilities and inspection points or other fittings for control and/or maintenance purposes may also be the other elements of a water distribution network (Defra, 2015). Finally, wastewater management systems broadly consist of a sewer network to collect the wastewater, and treatment works to transform the wastes to a condition where they can be returned to the natural environment. Wastewater management networks perform the key functions of collecting and treating wastewater, discharging treated effluent into the environment and disposing of biosolid sludge (Manning et al., 2016). In Britain, the infrastructure system consists of 624,000 km of sewer pipe and over 9,000 treatment works, which collectively process wastewater from about 96% of Britain's population. Treated effluent is discharged into waterways and coastal waters, and sludge is either digested, spread on agricultural land, incinerated to reduce the volume, or disposed of in landfills. Sewage treatment in Britain involves a significant consumption of energy, which results from the active aeration treatment processes frequently used to accelerate the natural breakdown of organic matter. The water industry consumes approximately 1% of the national energy budget; of this, 40% is used in wastewater treatment, the most energy-expensive component of the water industry, a proportion which will continue to increase unless treatment technologies are changed (Manning et al., 2016).

1.1.3 Complexity and interdependencies of infrastructure systems

In the previous section, several technical infrastructures as complex systems and their criticality for the economy and welfare of societies were introduced. It was also mentioned that understanding the interaction of components or/and sub-systems as well as the overall operation of these systems requires specialized knowledge due to the inherent complexity of these systems. These complexities largely developed due to the vast functional and spatial dependencies and interdependencies that exist across the infrastructure systems (Johansson and Hassel, 2010) as well as the inherent properties of technical infrastructure systems such as diversity, spatial distribution, variability as well as couplings and interactions. This section highlights the complexity and dependencies that exist in infrastructure systems.

1.1.3.1 Complexity

Generally, infrastructure systems are known to be Complex Adaptive Systems (CASs) (Rinaldi et al., 2001). Complex adaptive systems are defined as those systems which are composed of interacting, autonomous agents which include properties and behaviours (North et al., 2013). An agent is an entity with a location, capabilities and memory. The location expresses where the entity is in a physical space (e.g. a geographic region). The capabilities express what the entity can do from its location, such as a third rail carrying a high voltage. The memory of the entity defines what it has experienced, such as aging and fatigue. Memory is often shown in the form of agent state variables (Rinaldi et al., 2001).

From a CAS perspective, the agents aggregate, learn from their experiences, and adapt their behaviours so they are more suitable to their environment(s) and ultimately interact with and influence each other (North et al., 2013). In fact, each component of an infrastructure forms a small part of the complex network which creates the complete infrastructure. Past experiences affect all components and hence change often occurs because of learning processes. For example, rails slowly wear from abrasion of rolling wheels over them, and natural gas pipes and water mains age over time. Furthermore, elements of a system are able to individually learn from past experiences and adapt to future expectations. For instance, operating staff try to improve their performance and real-time traffic management systems find optimized traffic solutions. In a CAS environment, elements/agents not only aggregate and learn from their experience but also interact and synergize. Therefore, the simple aggregation of elements/agents cannot ensure the operation of reliable infrastructures. “This additional complexity exhibited by a system, beyond the simple sum of its parts, is called emergent behaviour and is a hallmark of CASs” (Rinaldi et al., 2001). “Agents communicate with one another as they operate in an environment. Each agent receives inputs from other agents and sends outputs to them" (Rinaldi et al., 2001). Principles of CASs apply to individual technical infrastructures as well as to a system of infrastructure systems interacting with each other. Therefore, the behaviours of agents/components (e.g. aggregation, adaptation and interaction) also appear across different infrastructures. These linkages or connections are called dependencies, which are explained in the next section.

1.1.3.2 Dependencies

Exploring the general case of various infrastructures connected as a "system of systems," infrastructures are frequently linked at multiple points through a broad range of mechanisms. Dependencies among infrastructures increase the overall complexity of the system of systems. The connections develop a complex network that, depending on the characteristics of its linkages, can create cascades throughout an economy and across multiple infrastructures.

Dependency is defined as "a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other" (Rinaldi et al., 2001 and Singh et al., 2014). In other words, the term 'infrastructure (inter)dependencies' refers to "relationships or influences that one infrastructure or one element in one infrastructure imparts to another infrastructure (or elements)" (Pederson et al., 2006). For example, a power plant as a sub-system of the power infrastructure requires solid and liquid fuels for power generators. The fuel needs to be transported from supply to demand centres by water, rail and road or pipelines. The power plant also requires water for cooling and emission control. This indicates dependencies of power on fuel, transportation and water infrastructures under a normal operating condition. In a normal operating condition, several infrastructures usually support the operation of an infrastructure (power in the above-mentioned example) and dependencies are considered to act in favour of economic prosperity. Furthermore, not only is power as an infrastructure supported by fuel, transport and water but it also supports them. This example indicates that bidirectional dependencies also exist between infrastructures and the term interdependency is usually used when the condition of each infrastructure affects or is interrelated to the condition of the other. For further examples of infrastructure (inter)dependencies among infrastructures refer to Rinaldi et al., (2001) and Sing et al., 2014.

Moreover, Rinaldi et al., (2001)defines six main dimensions for infrastructure interdependencies which potentially provide a foundation for developing interdependency metrics for infrastructure systems. The dimensions for infrastructure interdependencies shown in Figure 4 are useful in terms of facilitating the identification, understanding, and analysis of interdependencies. The following figures explain each dimension in detail.

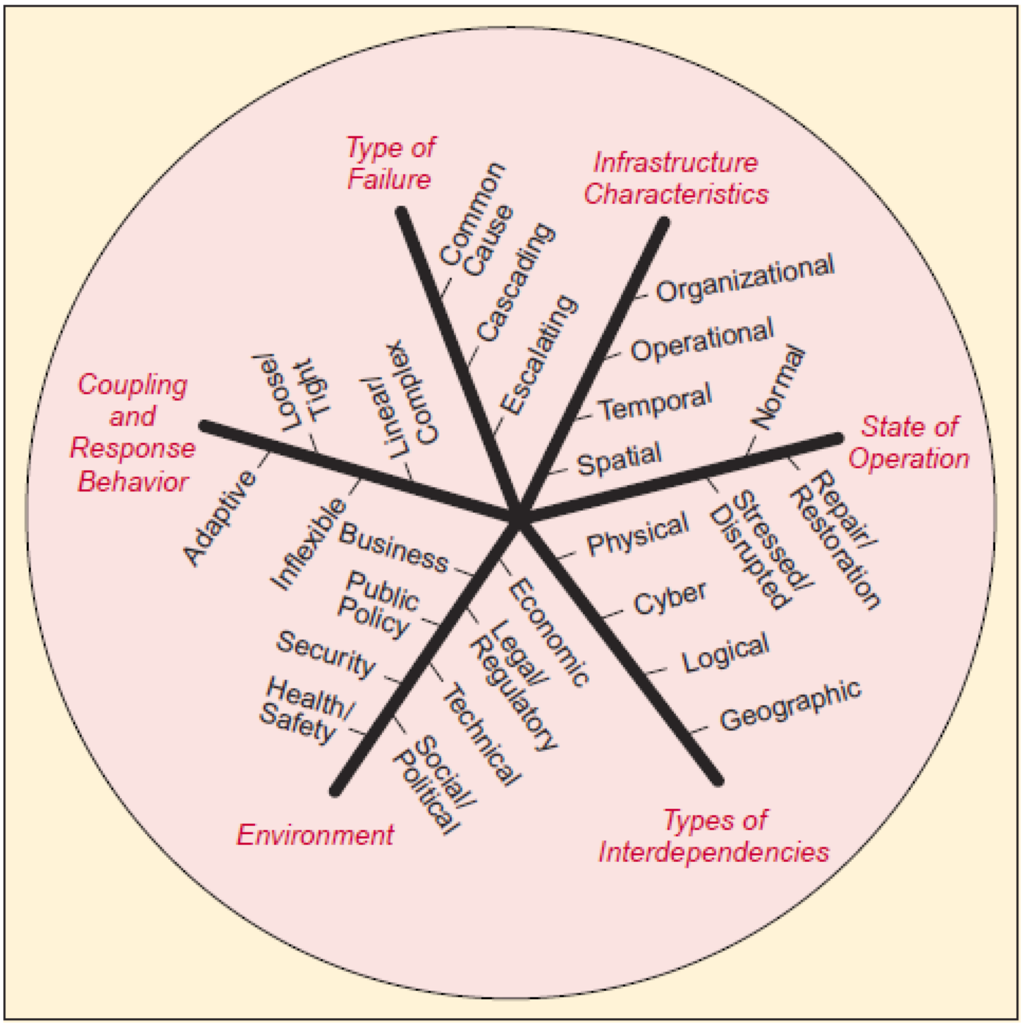


Figure 4 Six main dimensions and their subcategories to conceptually describe infrastructure interdependency (source: Rinaldi et al., 2001, figure 1.)

First, types of dependencies include; physical, cyber, geographic and logical. A physical dependency exists when one (sub-system of an) infrastructure provides physical output (such as transported commodity or power) for another infrastructure. Similarly, a cyber dependency exists between two infrastructures when the state of one depends on the information provided by another one. Furthermore, geographical interdependency is defined as the linkages that could be created between infrastructure systems when they are in relatively close neighbouring locations and events such as flood or fire can potentially cause simultaneous changes in these systems. In geographically interdependent infrastructures (e.g. a railway track and optical fibre cables) the state of one (sub-system of an) infrastructure is not influenced by the others in a normal situation. Eventually, two infrastructures are logically interdependent if the condition of each depends on the condition of the other in a way which is not a physical, cyber, or geographic connection (e.g. between major transportation projects and financial infrastructures) (Rinaldi et al., 2001, Kopylec, et al., 2007, Butts and Shenoi, 2011 and Petit et al., 2015).

Dependencies can be also described for different states of operation of complex systems; normal, disrupted and repair. Examples of dependencies in a normal state of operation have been provided previously. For a disrupted state, any cross-sectoral risk scenario between infrastructures, such as a disruption of power production due to a disrupted fuel supply chain, could be an appropriate example. During a repair state, for example, in the case of a train derailment, emergency and repair services require access to adjacent roads and even lands for faster recovery (Rinaldi et al., 2001, Butts and Shenoi, 2011 and Hall at al., 2016).

Furthermore, it should be noted that infrastructures are not only dependent on each other within the context of operation of systems. Organisational, temporal and spatial dependencies are the other key sub-categories of infrastructure characteristics as an interdependency dimension. For instance, regarding the spatial characteristic, the nature of dependencies largely varies within the engineering/local environment compared to regional, national and international scale. Given that infrastructures spread over physical spaces range in scale from local/rural areas to international, the scale of interest for analysis and investigation is largely related to the purposes of the analysis. Deliberations on national policies and securities may require detailed examination at the infrastructure, interdependent infrastructure, national, and international scales. Whereas, an analysis of direct and indirect dependencies between a power sub-station and a railway traction system requires a local or regional analysis (e.g. using a case study approach). Similarly, the infrastructure dependencies scientifically span a wide temporal range varying from seconds (e.g. the dependency of air transport on information and communication systems) to decades (e.g. the dependency of stability of road and rail earthworks on aging water mains vulnerable to leaking). Such dependencies are also referred to as short-term and long-term dependencies in the academic literature. Eventually, organizational aspects can play key roles in determining the operational characteristics of infrastructures (especially during a disrupted state), with important security and risk implications (Rinaldi et al., 2001, Butts and Shenoi, 2011 and Hall et al., 2016). For instance, good communication and shared contingency plans can significantly help recovery of dependent systems (e.g. road, rail, manufacturing and an import port) in the case of coastal flooding.

Regarding the type of failure within interdependent infrastructures, a cascading failure occurs when the failure of one infrastructure or one component can trigger the failure of other infrastructure(s) or components within them. For instance, a failure in electricity supply infrastructures may disrupt the operation of dependent infrastructure systems and their sub-systems such as railway traction substations. An escalating failure occurs when an existing disruption in one infrastructure can aggravate the failure of another infrastructure, typically in the form of increasing the severity of the failure or the recovery duration (Rinaldi et al., 2001, Butts and Shenoi, 2011 and Hall et al., 2016). For example, a disruption in a railway operation (e.g. due to derailment) can escalate due to a simultaneous disruption in a road transport network which results in the delay of the emergency/repair team's arrival. Finally, a common cause failure occurs when components of multiple interdependent infrastructures could be affected simultaneously usually due to geographical proximity (e.g. in the case of a flood or fire).

Moreover, regarding the coupling and response behaviour, the key coupling characteristics are "the degree of coupling (tightness or looseness), the coupling order, and the linearity or complexity of the interactions" (Rinaldi et al., 2001). Whether the infrastructures are adaptive or inflexible when stressed or disturbed is mainly influenced by the coupling characteristics and the nature of interacting elements/agents. For example, disturbances in the gas supply, unlike in the coal supply, will have almost instant effects on electrical generation. Therefore, electricity generation is tightly dependent on the gas supply chain while it is loosely dependent on the coal supply chain. Regarding the coupling order, whereas electric power directly contributes to the normal operation of the water supply system, the agriculture industry both directly and indirectly depends on electric power (i.e. through dependence on the machineries and the water supply). The direct dependency is considered as a first-order effect between systems whereas the indirect dependency is known as the second-order effect. “Linear interactions are those in an expected and familiar sequence of events, and those that are quite evident even if unplanned such as in a food supply chain, while complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and are either not visible or not immediately comprehensible such as chemical reactions in oil refineries” (Rinaldi et al., 2001). Furthermore, flexibility and adaptability of linkages and also agents in a CAS depend on numerous factors such as the availability of substitutes and backup systems as well as health and safety standards and training for staff (Rinaldi et al., 2001 and Hall et al., 2016).

Finally, another way of characterizing infrastructure interdependencies is to group them by several general concerns, including economic, social, technical, business, security, legal, etc, that shape how the environment systems evolve and operate. For example, tax imposed by governments on imported goods required for industries can significantly influence the dependency of infrastructures such as power on certain fuel types. Heavy regulations, privatization, profitability and the availability of a skilled workforce are examples of constraints imposed by different types of environment which influence the nature of infrastructure dependencies (Rinaldi et al., 2001, Butts and Shenoi, 2011 and Hall et al., 2016).

Therefore, a comprehensive view over infrastructures and interdependencies should acknowledge all the above-mentioned dimensions and evaluate the importance of each factor and determine whether they are worth inclusion in a more detailed analysis in the scope of one research.

The next section explains the importance of the railway sector as a sub-system of transport systems and as a significant contributor to the economy. This explains the reasons why this research focused on railway related dependencies at a sector level.

1.2 Railway sector

As previously stated, an individual infrastructure system contains a group of individual sectors or subsets (Refer to Table 1). For instance, the energy infrastructure contains the sectors of electricity, national gas, liquid and solid fuels. The electricity sector includes sub-sectors or networks of electrical generation, transmission and distribution, etc. (Pederson et al., 2006). Dependencies (links) exist between sub-sectors and sectors of an individual infrastructure as well as between different infrastructure systems. Links and interdependencies appear both between components (assets) of different infrastructures as well as the overall input and output of infrastructures.

In the case of transport systems, railways, road, aviation and shipping are individual sectors/subsets of transport networks. Among these sectors, railways are very important, inherently very complex and show interconnectedness with other infrastructure systems and their sub-systems (sectors). The following sections provide a summary of the significance of railways and the reasons they require special attention as well as examples of railway interdependencies and complexity.

1.2.1 The importance of railway systems

As previously mentioned in section 1.1.2.2, in general transportation systems provide a network of options to support the mobility of people and goods. The customers of transport systems (passengers and shippers) should have the ability to select a complete journey from the start point to the end, and to be offered transport options with differing profiles, costs and schedules. Consequently, the availability of an integrated multimodal transport system is essential and acts as a backbone in every developed society. Railways play a major and complementary role with respect to other transport modes (air, road and shipping) to facilitate integrated and end-to-end journeys for people and goods. Similarly, regarding other infrastructure systems, railways provide options for mobility of their goods (e.g. for businesses and manufacturing commodities) and their people (e.g. customers and staff). Hence, through dependencies, railways also contribute to providing essential services and profit to the economy (European Commission, 2018).

Moreover, government funds reflect the significance of any one sector regarding its economic and social benefits. For example, the UK Government clarified its resolution to invest in public transport, mainly in high speed rail, to rebalance the economy and to reduce regional inequalities. It is explained that the transport system should act as an engine for growth and radically reshaping economic geography to help bridge the North-South divide that has limited for too long growth outside the South East. In the UK, the government reports show that the highest benefits from investment in transport domestically were likely to result from focusing on reducing congestion and relieving bottlenecks on road and rail networks. While globally, increasing international connectivity results in the highest benefits. It is estimated that, "if left unchecked, the rising cost of congestion would cost the UK economy an extra £22 billion per annum by 2025" (House of Commons, 2011). In addition, one investment often produces further demands. For example, it was argued that to achieve the full economic benefits from HS2 (High Speed 2), improvements to regional rail services in the West Midlands and Yorkshire would be necessary (House of Commons, 2011). Figure 5 shows how UK transport spending—capital and resource, at all levels of government—more than doubled, rising from £11.2 billion in 1999–2000 to £23.1 billion in 2009–10 (at 2009–2010 prices).

Based on data from Network Rail (the infrastructure owner of most of the UK's rail infrastructure) "20% of all the UK's new infrastructure spend is on rail infrastructure and £4 of economic benefits is returned for every £1 invested from some of Network Rail's major projects" (Network Rail, 2018). Also, from a social benefit perspective 216,000 people work at the rail sector and its supply chain, with £10.1 billion in Gross Value Added (GVA) contributed to the economy each year. The total capacity of freight trains which deliver goods all over the UK equals that of 7.6m lorries at the road every year. Generally, from a social perspective, the railways cross most of UK and impact millions of lives through social development, creating jobs and transport links and providing other benefits for local communities (Network Rail, 2018).

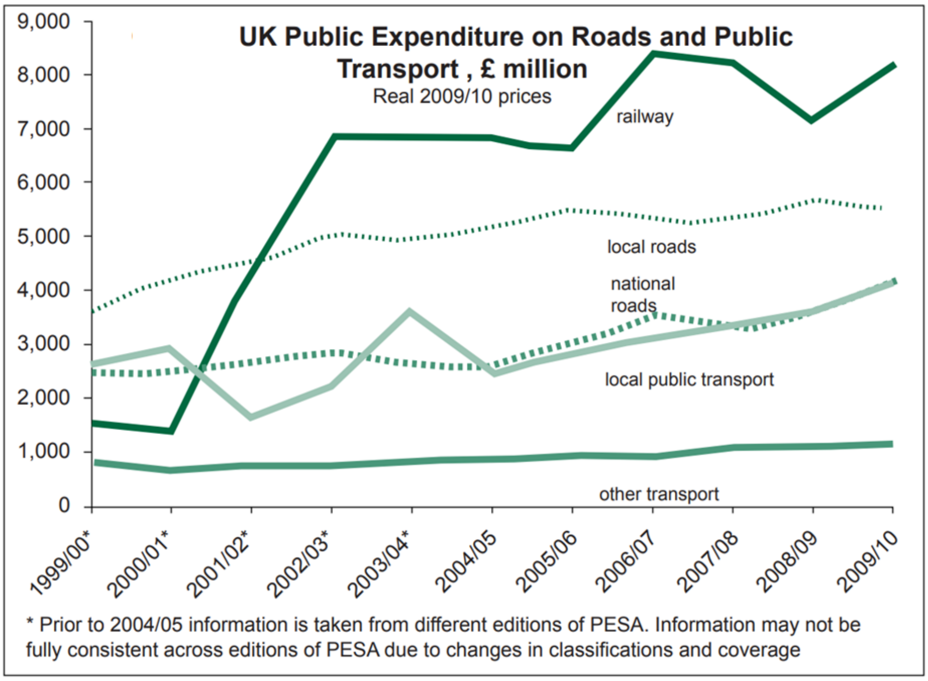


Figure 5 UK public expenditure on public transport by different sectors (House of Commons, 2011, chart 1.)

Transport is the main contributor of greenhouse gas (GHG) emissions in the UK after major declines in emissions from the energy sector. However, the Rail Safety and Standards Board (RSSB) confirmed in 2019 that considering the heavily used journeys both passenger and freight railways remain among the lowest carbon form of transport. This agrees with the GB transport statistics for 2018 (DfT, 2018b). In February 2018, the UK government challenged the rail industry to remove all diesel-only trains from the network by 2040 and to provide a vision for how it will decarbonise. The data shows that approximately 63% of greenhouse gas emissions in the rail industry were directly attributable to traction energy (almost 60% of which were attributable to diesel). 21% of the remainder were produced within subsystems dedicated to developing and managing the rail network and movements on it, and 13% were attributable to station and depot operations (RSSB, 2019). Note, in general, the use of the terms systems and subsystems (or similar concepts e.g. infrastructures and sectors) depends on the viewpoint taken. An entity which is regarded as a system by people who developed it might be regarded as a subsystem by people who use it as part of their system. This concept is known as the nested systems concept, according to which "systems are themselves built up of smaller systems (that themselves are built up of even smaller systems and so on)" (BS EN, 2017).

Acknowledging the significance and benefits of railways for the welfare of a nation (economic, social and environmental benefits), an investigation of its dependencies (especially at operational environment) with other infrastructures that may result in risks against the reliability and safety of this sector would be necessary. The next section briefly introduces the complexities and interdependencies that exist for railways in general with a specific interest in the UK railways.

1.2.2 Complexities and interdependencies in railway systems

In the previous sections, complex adaptive systems were introduced and elaborated on. Considering that a complex system is difficult to understand because it has a lot of parts that are all connected in different ways, railway systems are inherently very complex. Figure 6 illustrates the complexity of the railway systems based on four main determinants of complexity. Determinants are known as co-acting factors or issues that have the potential to influence a situation (Schmid, 2018). In order to explain the complexity of railways, the determinants can be explained as variability, dispersion, diversity and internal interconnectedness which result from the nature of coupling and the nature of interaction in complex systems. Broadly speaking, contradictory agendas and conflicting requirements by stakeholders, challenges of interoperability, the role of ergonomics in incidents, the effect of weather on the interaction of wheel-rail interface and railway upgrade programs are a few implications of technological, organisational and operational complexities at railways (Schmid, 2018).

First, variability is defined as the determinant indicating the act or state of varying in time. Railway examples include: variable quality and performance of the railway's earthwork, variable staff performance, variable wheel-rail adhesion and variable passenger behaviours. Although the above-mentioned examples mainly include the variability in the system caused by internal factors, external factors as well can cause complexity in terms of variability in time. Operational impact of weather, demand variation and economic cycle impact, stakeholder vacillation, subsidy regime variation and impact of connecting services are all examples of external variability in railway systems. Furthermore, most railway systems are linear and spatially distributed along thousands of kilometres. Distribution and linearity result in complexities and difficulties to design, install, operate, manage and maintain assets (e.g. trains, bridges, tunnels, drainage and signalling assets). It is challenging to provide effective customer service and to supervise and manage staff effectively and hence in practice many decisions need to be taken locally. Regarding the diversity in railways, first many types of subsystems are involved in railways which are broadly illustrated in Figure 7. Furthermore, the variety and diversity at a component level is high as well. The examples include; steel and concrete structures, electrical machines, sensor and effectors and precision mechanical systems including the various properties such as the lifespan of assets for each subsystem/component. Additionally, the nature of coupling and interaction between railway sub-systems is also shown in Figure 7. On the other hand, sub-systems and components can couple together tightly or loosely to successfully perform various functions for the railway systems. Wheel and rail interface, pantograph and overhead line interface, and switches and crossings are a few examples indicating the nature of coupling in railways. Similarly, sub-systems interact in linear or complex ways to facilitate normal operation and maintenance of railways. Such interactions could be shown using arrows in Figure 7 (Schmid, 2018).

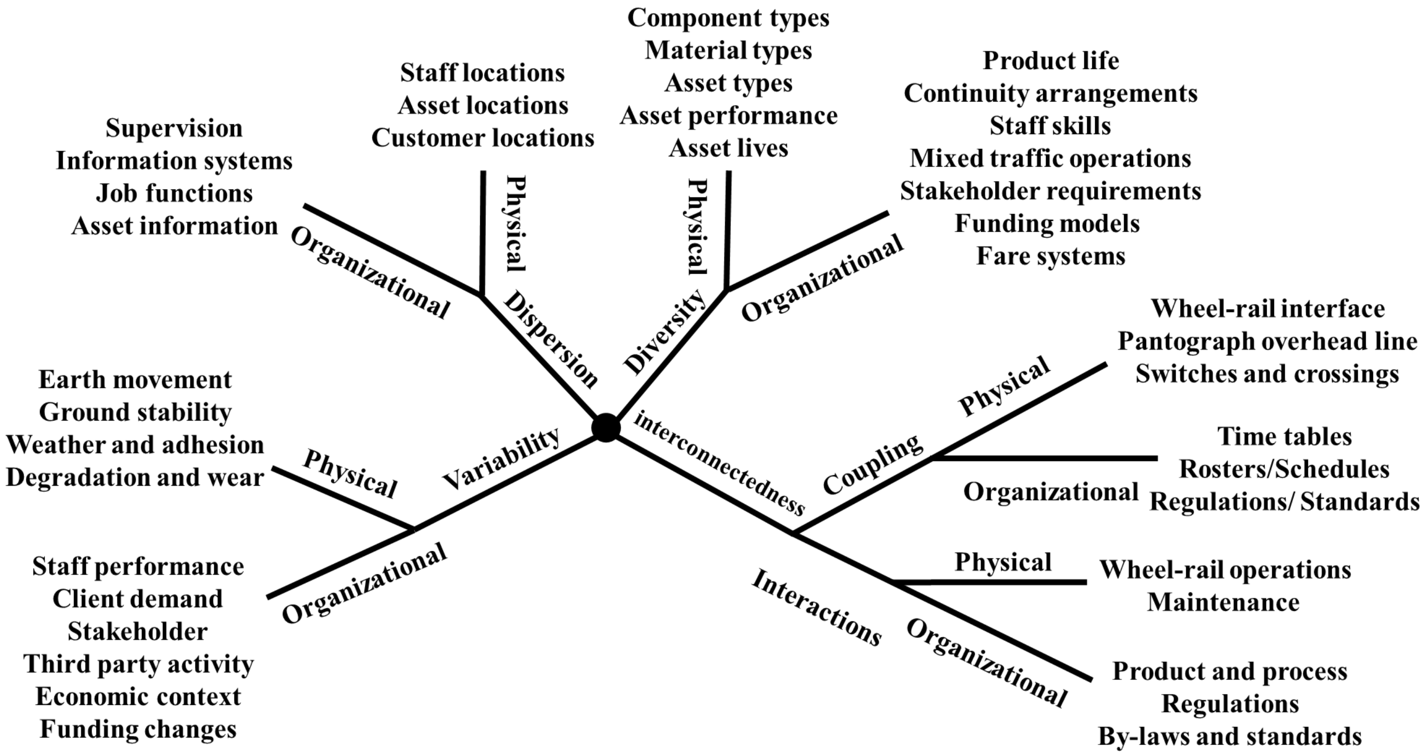


Figure 6 The determinants of railway complexity with several examples- adapted from Schmid, 2018

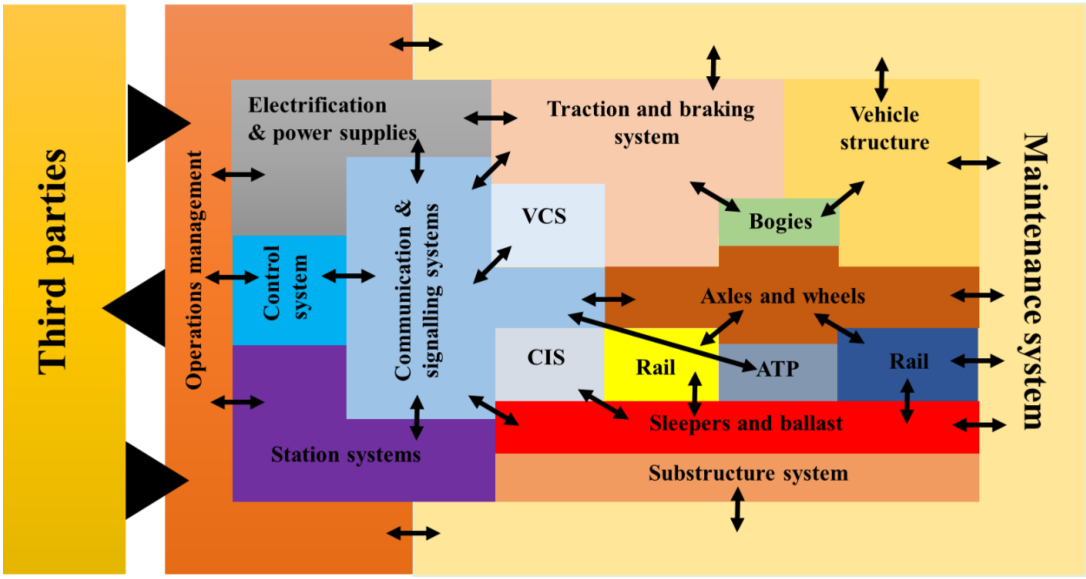


Figure 7 Primary illustration of railway sub-systems and their interactions - adapted from Schmid, 2018

Note that for the understanding a complex adaptive system, one should always assume that in theory or/and in practice, each system is defined by a traditional boundary inside which the group subsystems and elements coexist. Anything outside of a system's boundary can be delineated as the surrounding natural environment and the external systems (e.g. electricity generation systems) which are dedicated to other purposes. Similar to the interconnectedness defined above for inside railways, the infrastructure interdependencies can be described as the linkages that a railway system has across its traditional boundary with the external systems. On the other hand, because railways are variable, dispersed and diverse, such interdependencies with external systems would appear in different dimensions as demonstrated in Figure 4.

Moreover, Pant et al. (2016) argues that the railway network needs resources from other infrastructures to be capable of operating its assets. Figure 8 shows the key infrastructures that supply the resources for operating the critical railway assets such as traction and signalling. The study illustrates key (inter)dependencies across infrastructures according to the operational requirements of assets. The solid black arrows illustrate that some of the infrastructures provide resources directly to the railway network. Where a railway asset indirectly requires resources from some infrastructures to operate the dashed black arrows represent such indirect connections.

The direction of the arrows in each link shows the direction of resource flows across infrastructures.

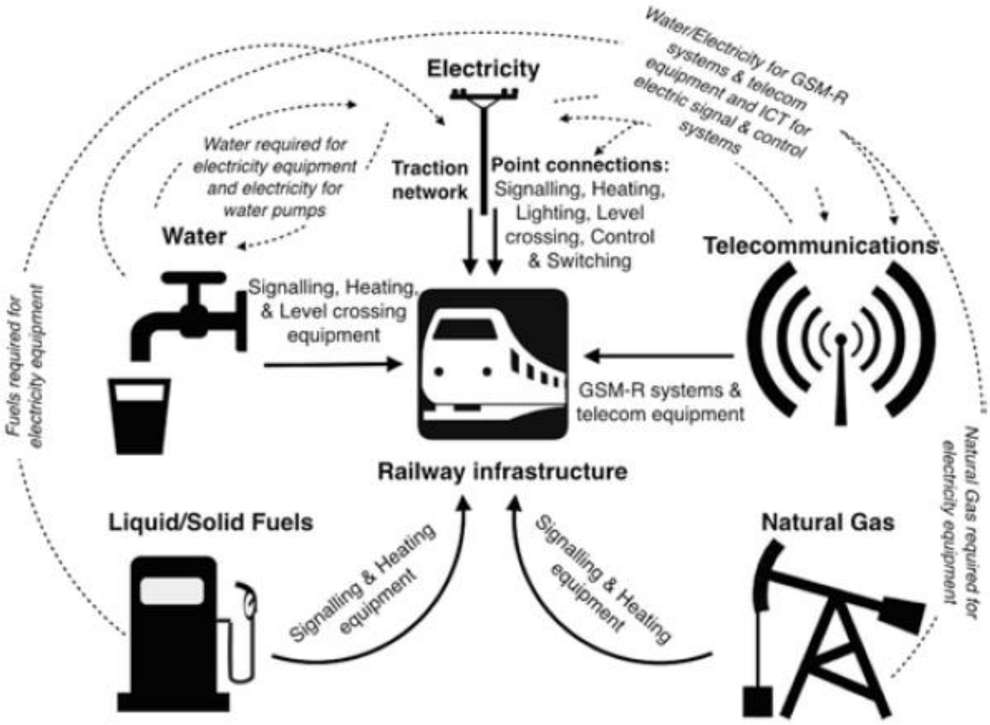


Figure 8 Interdependency mappings between infrastructures that are required for an operational railway network (source: Pant et al., 2016, figure 4.)

Acknowledging the importance of infrastructure interdependencies on railways, RSSB (2016) argued that the interdependency of the railway subsystems on external systems can be explained using an analysis framework. This framework relates one railway subsystem to an external system through several key channels including people, material, machinery/ devices, power/ fuel, communication/information/data, and other flows (including small elements such as chemicals in water). Figure 9 shows the railway dependency analysis framework. These channels represent the flow of people, resources and information which exist outside railway premises but are required for the railway system to operate. For example, drivers are required to operate trains, but they live outside railway premises and thus must commute. Therefore, the channels shown can explain the dependency of a railway subsystem on an external system. For all the subsystems to meet their overall goals, these channels and interacting parameters need to exist in the right conditions. Several examples of this include:

- For a passenger train (as a component of the rolling stock subsystem) to operate, there needs to be a driver (person) who needs to arrive at a depot in time and a right amount of electrical power supply(fuel/power).
- Some track maintenance work (as a component of the track subsystem) requires machinery (machinery/device) hired from external companies and transported to railway premises, and replacement materials (materials) as well as workers (people) and fuel for machinery (fuel/power).

These require the use of a variety of external systems, machinery and power sources under the right conditions of other factors such as the voltage and current of electrical power supply.

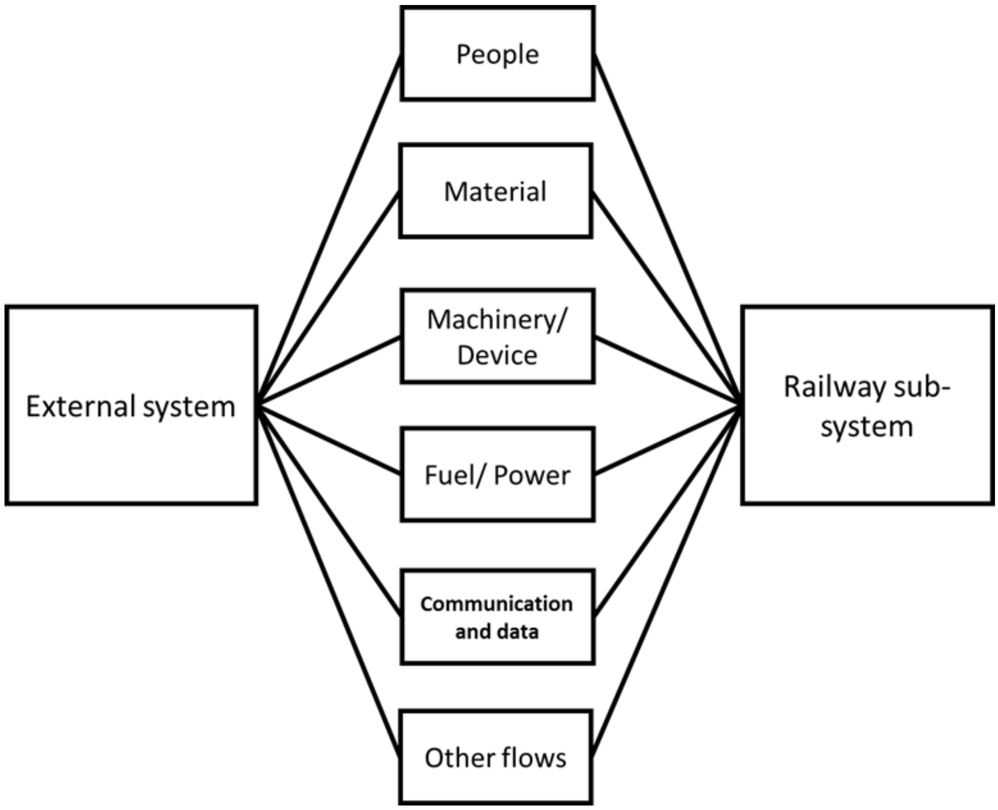


Figure 9 Dependency framework for railways interdependencies (source: RSSB, 2016)

Furthermore, RSSB (2016) found the flows of people, resources and information between the railway subsystems and the external systems to perform the following functions:

1. Running the service (directly)

2. Accommodating the movement of customers and goods
3. Allowing access for people (drivers, managers, maintainers and technicians) and accommodating their movement
4. Facilitating electric-power transmission
5. Facilitating maintenance activities
6. Facilitating communication
7. Completing end to end journey
8. Facilitating ground water movements to stabilize geotechnical structures
9. Draining the water from railway premises to enable rail infrastructure to operate properly
10. Providing water to be used to serve customers and railway staff and for equipment
11. Providing natural environment platforms for assets to operate properly
12. Transfer of knowledge and data between skilled engineers to design and develop the railways.

Considering these functions, Table 2 shows the dependencies of the railway system on the external systems. For example, the table shows that: the track subsystem is dependent on the water-related system in terms of supporting the environment to enable the track to operate as required. The following section discusses the dependencies in detail.

Table 2 Characterisation of infrastructure interdependencies at railways (source: RSSB, 2016)

		Railway subsystems				
		Track	Civil engineering infrastructure	Signalling and control system	Electrical power supply	Rolling stock
External systems/environment	Electrical power system	5	5	5, 6	4, 5	1, 5
	Water-related system	9, 12	8, 9, 10, 12	9, 10, 12	9, 12	9, 10, 12
	Transport system	3	2, 3, 7	3	3	2
	Fuel supply system	5	5	5	5	1
	Natural environment	11, 12	11, 12	11, 12	11, 12	11, 12

Acknowledging the fact that railway systems can potentially provide valuable examples for investigating infrastructure interdependencies, the next section of this chapter explains the prime motivation of this research.

1.3 Motivation for this research

As previously discussed in section 1.1.3, the critical infrastructures are highly interconnected and interdependent and hence what happens to one type of infrastructure can directly or indirectly affect other types of infrastructure. Be it through direct connectivity, strategies and functions or spatial proximity, infrastructures and their sectors interact. At a sector level, railway systems, for example, are highly complex and complicated, while their criticality for the economy and wellbeing of nations cannot be neglected. Considering the above-mentioned background and the existing knowledge and practice, this research undertook two case studies to improve the understanding of the dependencies that exist but are little understood between railway systems and other infrastructure systems. This work assumed that the infrastructure system as a system of systems is not a disconnected series of isolated assets but instead several cross-sectoral links and hence challenges. The following are the main motivations for carrying out this research:

1.3.1 Gaps in the academic knowledge

Academic studies argue that technical infrastructures (e.g. energy, transport, water, waste and information and communication technology) have evolved over centuries, being managed piecewise. These systems are mostly planned and implemented in isolation from one another, ignoring the dependencies and relations to other infrastructures (Johansson, 2010, Otto et al., 2016 and Oughton et al., 2018). Therefore, the interactions between infrastructures have been intensively studied for the last few decades. (Current studies are critically reviewed in Chapter 2.) However, research related to the topic of infrastructure interdependency still focuses on a limited number of dependency scenarios between infrastructures and therefore a gap in the knowledge exists. Many interdependency-related scenarios especially at local/engineering and sector level have not even been acknowledged, let alone investigated properly within the scope of infrastructure interdependency-related research. Consequently, there is a serious lack of scientific methodology for the understanding and evaluation of some of the dependencies. Bridge strikes, trespassing, regional coastal or urban flooding, multi-modal transport and human resources, issues around supply chains, level crossings, issues around adhesion due to weather conditions and other weather-related scenarios are examples of interface-related risks which have not been investigated from an interdependency and "system of systems" perspective. Hence, in the first place, understanding the little-known infrastructure dependencies and the potential consequences of them is the main motivation of this research. Therefore, this research includes development of analysis methods and simulation tools for evaluating several little-known dependency scenarios between railways and other infrastructures.

1.3.2 Uncertainty and risk

Infrastructure interdependencies introduce layers of complexity, uncertainty and risk to planning, design and operation of infrastructures. If interdependencies within the context of vulnerability (e.g. in a disrupted state of operation) are not identified and hence not evaluated properly, the risk management of the infrastructures in many cases must be led by traditional reactive approaches. A prime example is when a coastal flooding disturbs interconnected systems (e.g. port, rail, road, utilities and services) at a regional scale, if infrastructure operators and authorities have no shared plan for contingency. Better identifying, understanding and analysing of interfaces and interdependencies can act as initial steps towards providing several benefits. First, it can facilitate development of knowledge and data sharing platforms between industrial sectors. Then it can be used to numerically evaluate potential cross-sectoral risks as well and hence help the proactive planning and management of infrastructure systems. The ideal and final goal of an interdependency analysis would be to identify significant risks to critical systems, arising from interconnection, and effective mechanisms for mitigating those risks.

1.3.3 Convergent current and future challenges

In both the UK and other advanced economies, infrastructures are facing serious challenges. These challenges threaten a society's ability to continue to provide their essential services that support nearly all aspects of daily life (Hall et al., 2012). Changing the demand for infrastructure services from an ageing infrastructures system, increasing degrees of complexity between these systems, significant investments needed for renewing infrastructures, meeting emissions reduction commitments, ensuring secure supplies, ensuring individual and economic security and maintaining a competitive economy are examples of the current challenges. Adaptation to a changing climate, demographic changes (e.g. an aging population), regulatory and policy changes and a changing technological environment are examples of the future challenges which infrastructure systems are facing. It is clearly impossible to effectively examine or understand the performance and behaviour of any given infrastructure regarding the challenges in isolation from the environment or other infrastructures. Rather, we must consider multiple interconnected infrastructures and their interdependencies in a holistic manner. The complexity of the infrastructures and their interactions prevent us from knowing a priori how these interactions will influence individuals, regions or nations (Brown et al., 2004). Therefore, more understanding of complexity and dependency at all levels, scales and dimensions (especially where gaps of knowledge are observed) facilitate adaptation to the current and future challenges.

1.3.4 Other incentives

In the UK, the government has been encouraging each infrastructure sector to consider climate change risks but advocates that one of the challenges in climate change mitigation and adaptation is dealing with risks that the impacts of climate change pose to infrastructure interdependencies (Stationery Office, 2011). The Royal Academy of Engineering (2011) argued that infrastructure systems are developed in a highly interdependent way and if one infrastructure system is at risk, so are the rest. For example, if floods damage an electricity supply infrastructure, all other interdependent infrastructure systems can be affected, causing a cascade of failures. Furthermore, worldwide, several large-scale research initiatives have been started into developing new suites of infrastructure analysis and modelling tools. Examples include a US National Research Council report on Sustainable Critical Infrastructure Systems, Dutch programmes on Next Generation Infrastructure and Knowledge for Climate, the UK Infrastructure Transitions Research Consortium (ITRC) and the Australian Critical Infrastructure Protection Modelling and Analysis (CIPMA) programme. However, many challenges remain to be addressed due to key considerations such as the availability of good quality comprehensive data and information, which are believed to be the core of developing long-term robust and economically sustainable infrastructure investment plans (Barr et al., 2013 and Rinaldi et al., 2001). This indicates that in addition to the knowledge, development of datasets and tools are also still at an early stage and further work is required.

Moreover, the Commission of the European Communities stated that "the disruption or destruction of critical infrastructures in each community would affect two or more Member States or a Member State other than that in which the critical infrastructure is located" (EN, 2006). This is because cross-sectoral effects may result from interdependencies between interrelated infrastructure. Therefore, there is a requirement to improve the protection of such critical infrastructures through joint efforts and shared framework. One major aim is "promoting and supporting the development of minimum-security standards, exchange of best practices, risk assessment tools, methodologies to compare and prioritise infrastructure in different sectors, analysis of vulnerabilities and interdependencies on protection of critical infrastructures" (EN, 2006). The document also gave a clear reminder that "the identification and analysis of interdependencies, both geographic and sectoral in nature, will be an important element of improving critical infrastructure protection in the EU". This ongoing process will feed into the assessment of vulnerabilities, threats and risks concerning critical infrastructures in the EU. It also promoted consulting and involving relevant stakeholders to facilitate the implementation of the infrastructure-by-infrastructure and sector-by-sector approach to critical infrastructure protection (EN, 2006).

The above indicates an ongoing universal incentive for identification and investigation of infrastructure dependencies which played a major role in terms of motivation for the current research.

1.4 Aim and objectives

The main aim of this work is to investigate the interdependencies between several technical infrastructures and railway systems. In order to fulfil this aim, the following objectives were set:

1. Critically review the existing knowledge of infrastructure dependencies and the methods to investigate them
2. Describe a suitable approach to investigate little-known dependencies
3. Investigate interdependencies between railway systems and power generation systems using publicly available sources and industrial contacts within a case-study framework
4. Investigate interdependencies between railway systems and urban water systems using publicly available sources and industrial contacts and further develop a generic numerical model as a tool to evaluate the dependency
5. Draw conclusions and provide a brief overview of directions for future research

The benefit of this research is the creation of a tool that supports the improvement of the resilience of the railway system to risks that may initiate outside the traditional boundaries of the railways.

1.5 Structure of the thesis

This thesis presents a background of the investigated topic, followed by an introduction of the aim and objectives of the investigation. In chapter 2, a critical literature review is carried out with an emphasis on studies and research that focused on infrastructure dependency and the methodologies these studies employed. In Chapter 3, the overall approach of this research is explained. Chapter 4 presents a case study which aimed at understanding the dependencies between railway systems and power production systems. Next, in chapter 5 a risk-based interdependency between railway infrastructure and urban water system is investigated using a case study approach and numerical simulation. The overall discussion and the conclusive argument of the thesis is included in Chapter 6 while the conclusions of this thesis are drawn in Chapter 7.

Chapter 2 Overview of infrastructure dependency: a literature review

Much effort is currently being devoted to the investigation of infrastructure dependencies. The aim of this chapter is to provide an overview of the existing academic literature and discuss the gaps that may exist in the knowledge. Therefore, section 2.1 reviews different research topics and perspectives that exist within the subject of infrastructure dependency and then section 2.2 discusses the different approaches and models that are commonly employed in the academic literature to investigate infrastructure dependency.

2.1 The existing perspectives on infrastructure dependencies

In the last few decades infrastructure dependency has been the subject of many research studies. These studies can be grouped based on different viewpoints/perspectives of their research focus and the main context. This section summarises and critically reviews the existing studies within each group.

2.1.1 Conceptual and qualitative perspective

Several large-scale projects have highlighted qualitatively the big picture of infrastructure interdependencies. Hall et al. (2016) and CTS (2009) constantly state the significance of investigating infrastructure interdependencies, especially within a national "system of systems" perspective. It is argued that national infrastructure systems are becoming larger and significantly more interdependent, hence even small changes in one infrastructure can have important effects on the output of the overall system (e.g. as an economy). As is also mentioned in Chapter 1, the combined effect of ageing infrastructures, increasing demands together with growing interdependencies and complexity, as well as a changing climate, leads to systematic weakening of the resilience of infrastructure systems. Such shifts have important implications for the resilience and sustainability of infrastructure systems, which need to be acknowledged (see McDaniels et al., 2008 and Ouyang et al., 2012 for a thorough definition regarding the resilience and sustainability of infrastructure systems). On the other hand, interdependencies can also result in prosperity and provide opportunities, especially in terms of the technological change. Many promising technological innovations, for example, smart grids, electric vehicles or high-speed rail networks, closely depend on the integration between different infrastructure networks (e.g. IT and transport/electricity). The above studies state that although such interdependencies potentially provide many opportunities, they also introduce additional layers of complexity to the national infrastructure system, for which the long-term sustainability impacts are not well understood. Therefore, such interdependencies need to be considered in a reliable way in infrastructure planning and design. The very first step towards such consideration and acknowledgement could be to understand infrastructure interdependencies conceptually before attempting to evaluate them quantitatively. Thus, from the conceptual/theoretical (or qualitative) perspective, several writings comprehensively characterise the various dimensions/factors and concepts which could also help as evaluation criteria for infrastructure dependencies (e.g. Rinaldi et al., 2001, Little, 2002, Rinaldi, 2004, McDaniels et al., 2007 and Hall et al., 2016). As briefly mentioned in Chapter 1 (refer to Figure 4) several dimensions/aspects were usually used by these studies to describe the infrastructure interdependencies namely:

- types of dependencies (physical, cyber, geographic and logical) for which there are distinct characteristics that are not mutually exclusive,
- state of operation of infrastructures (normal, disrupted and repair) which is a function of many interrelated factors and system conditions,
- infrastructure characteristics (spatial, temporal, operational and organisational) which are key features for understanding dependencies and vary greatly in different analyses,
- types of failure (cascading, escalating and common cause) which are modes of failure fundamentally different to failure within a single (isolated) infrastructure, since interdependencies are key to the generation and/or propagation of these types of failure,
- coupling and response behaviour (linear, complex, loose, tight, adaptive and inflexible) which directly influences whether an infrastructure is adaptive or inflexible when perturbed or distressed and lastly
- the environment (social/political, technical, legal/regulatory, economic, health/safety, security, public policy and business) which is the framework in

which operators establish goals and objectives for defining and viewing their businesses, model and analyse their operations, and make decisions that affect infrastructure operations (Rinaldi et al., 2001, Hall et al., 2016 and McDaniels et al., 2007).

The examples of these characteristics (or dimensions as they are termed by Rinaldi et al., 2001) have been previously explained and examples were provided in chapter 1, since they are generally useful in providing a comprehensive view regarding the topic of infrastructure interdependencies. Rinaldi et al. (2001) who provided the only complete conceptual academic literature on infrastructure interdependencies, emphasize that such categorisation can effectively facilitate characterisation of dependencies. Although categorisation is useful, it can be argued that attempting to group dependencies based upon the meaningful patterns observed within them cannot necessarily guide the scope of a research in terms of choice of approach and modelling requirements. However, conceptualisation in general can highly support the systemic and intensive thinking needed for examining any infrastructure-dependency related problem.

Moreover, Rinaldi (2004) adds that classification of interdependencies could be also useful in terms of analysing them and hence for their modelling and simulation. Rinaldi (2004) argues that several other factors such as social and psychological elements, company-specific operational procedures and stakeholder concerns can also affect/influence or even complicate the requirement of interdependency-related analyses (including modelling and simulation). For instance, since infrastructures are socio-technical systems, social networks and behavioural responses can influence infrastructure operations. For example, in the case of the transport system, since people travel to take part in various activities (e.g. work and leisure) an effective understanding of interdependencies between the transport and other sectors requires researchers to better understand these activity patterns and analyse accordingly. Moreover, company-specific procedures (such as contingency plans) influence the state of an infrastructure during an or emergency and may affect coordination among various infrastructure owners, while in many cases there are no cross-sectoral shared recovery plans. Also, stakeholders sometimes have divergent or even opposing motivations and concerns which may affect the understanding of the dependencies. For instance, while a road system may always be concerned about keeping the highways and roads clear and in a normal operating condition, a rail system would require a road closure to carry on engineering works which cannot be completed during the daytime. For the qualitative factors and element highlighted by this study, it can be argued that a more comprehensive list of examples related to various infrastructures could be included to further clarify the concepts.

Note that the conceptual studies usually focus on the qualitative investigation of dependencies on an abstract level and provide real-world examples for each dimension/factor and/or evaluation criterion of infrastructure dependency. They also demonstrate the importance and complexity of the topic. Most importantly, they delineate the framework and resolution for other groups of studies (with different research perspectives) that are explained in the following sections. This means that other infrastructure dependency research usually focuses only on one or several dimensions or evaluation criteria defined by the first group (conceptual studies) at a higher resolution/detailed level. For instance, one study may only focus on infrastructures in an economic environment on a long-time scale and at a national scale (e.g. Hall et al., 2014), whereas another may focus on a technical environment on a short-time scale at a regional level (e.g. Johansson and Hassel, 2010). Therefore, it is true to say that conceptual and qualitative studies have motivated other groups of research on infrastructure dependency and made provisions for better understanding of the subjects and quantification of the dependencies. Moreover, this group (conceptual studies) can inform strategies and policies and provide recommendations for governments to protect critical infrastructures. The recommendations usually include encouraging data and information sharing mechanisms between owners/managers of infrastructures as well as initiating new research and development programs (Ouyang, 2014). However, conceptual studies on their own cannot provide a comprehensive decision support tool for an economy where quantified evidence regarding the effect of one sector on another is necessary.

As for the studies focusing on dependencies related to transportation and/or railway systems, Otto et al. (2016) conceptually explained the transportation and communication infrastructures as the two systems by which their sectors (e.g. railways and road in transportation) connect different markets and businesses by physically moving elements and transmitting information respectively. Ibáñez et al. (2008) summarised the interdependencies between electricity and transportation infrastructures in terms of demand, location, cost, environment, storage and many other factors. The study described how the transportation and energy systems interact mainly at two ultimately interdependent stages of operation and investment. Ibáñez et al. (2008) explained that while the transportation infrastructure requires the energy infrastructure for fuel, the energy system requires the transport of raw bulk energy sources such as coal or natural gas. The cost of meeting these two demands ultimately affects the price of energy and transportation for consumers. Like much other conceptual research, this study described the dependencies between the two infrastructures and the factors that may affect them at an abstract level. Considering the infrastructure systems at a national scale and, therefore, treating the whole transportation system as a solid infrastructure, ignoring its sectors, the railway system (including passenger and freight) as a major transport sector with critical contribution to the economy has not been discussed. This indicates that the scope and resolution of infrastructure dependency-related studies significantly vary depending on the scale for which they conduct the investigation (for example, national economic environment rather than regional technical environment).

Rinaldi et al. (2001) used a conceptual framework to explain the potential effects and complexities of interdependencies of United States national infrastructure systems. As an example, Figure 10 conceptually shows the infrastructure dependencies between electric power and other critical infrastructures including the railway sector and other transport sectors. Similar figures were not provided to demonstrate other dependencies such as those between rail and telecom/water etc.

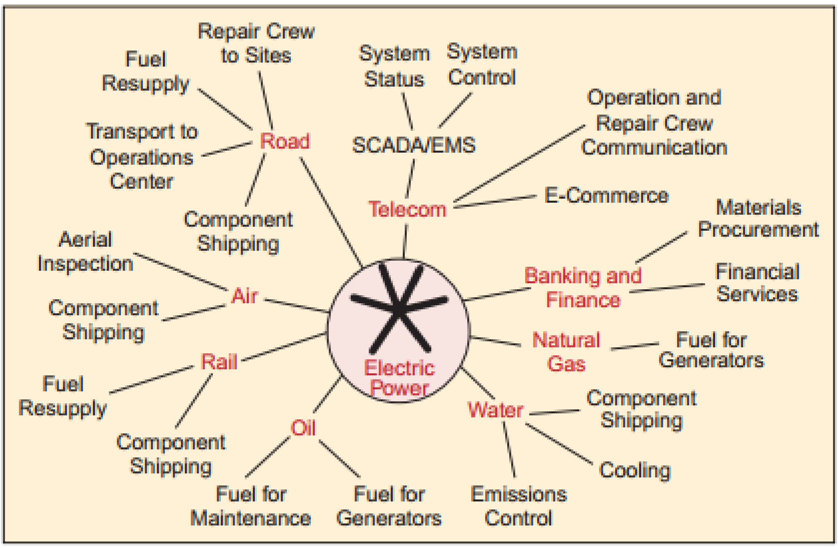


Figure 10 Example of electric power infrastructure dependencies (Rinaldi et al., 2001, figure2.)

Rinaldi et al. (2001) highlighted the following (inter)dependencies for the railway system as follows:

- Electric power infrastructure system depends on railway transportation to supply fuels.
- A railway network and a coal-fuelled electricity generation plant are physically interdependent. Each infrastructure supplies commodities that the other needs to operate. The physical interdependency indicates that the state of one infrastructure is dependent on the material output(s) of the other. Railways transport coal, fuel and large repair and replacement parts to the electricity generators. On the other hand, the electricity which has been generated by power plants powers the assets of the railway system (i.e. signals, switches, control centres, stations). Also, in case of an electrified railway system, the electricity directly powers trains. This means that the failure of one infrastructure system can lead to a failure of other infrastructure systems because the two are interdependent.
- Transportation systems including (freight) railways move the components of the other infrastructure systems including water systems, oil and gas systems, electric power systems and telecommunication systems, while railway systems depend on telecommunication systems for managing the flow of the trains, passengers, goods and staff. This indicates a cyber dependency, which means

that the state of one infrastructure depends upon information transmitted through another infrastructure.

- The oil infrastructure system provides fuels and lubricants for different railway sub-systems such as rolling stock, stations and train depots.
- Telecommunication cables and electric power lines often follow the railway rights-of-way. This creates a geographical dependency between the railway system and telecommunication and electrical power systems. “Infrastructures are geographically interdependent if a local environmental event can create state changes in all of them” (Rinaldi et al., 2001).

Furthermore, as for the more recent studies regarding the interdependencies in railways, RSSB (2016) qualitatively identified and explained various types of linkages between railways and external infrastructures at a more technical and local environment. As previously explained in Chapter 1, the study conceptually explained the dependency of different railway sub-systems on several external systems. The concept of “flows” across different physical systems was used to explain the connections and linkages, primarily with the purpose of understanding the vulnerability of railways in a changing environment (e.g. climate change and weather effect). The highlighted dependencies in this study are a summary of the flows that may need attention because of their potential importance for industrial practitioners and it needs to be noted that future large-scale studies are needed to compile a more complete dependency list. The identified flows between different subsystems (including track, civil engineering infrastructures, signalling and control, electrical power supply and rolling stock) are summarised in the following tables (see Table 3, Table 4, Table 5, Table 6 and Table 7):

Table 3 The identified flows/linkages between the track subsystem and external systems (source: RSSB, 2016)

		Track
External systems	Electrical power system	Track maintenance equipment and machines depend on electric power to function. Equipment such as point actuators, point heating systems, etc. requires electrical power to function.
	Water-related system	Disruption in external water mains, flood defence systems, watercourses and rivers can cause flooding of track assets. Water mains and rivers can potentially act as pathways to transfer external risks (such as chemical pollutants) to track systems. This can affect the durability of the track components and interrupt the maintenance practices. Long-term changes in ground water systems can cause large impacts on the structure of the track.
	Transport, communication and supply chain system	Access to sites and depos is dependent on local roads and public transport. Entry routes (e. g. local roads) to track for machinery and staff are limited due to congestion and potential obstruction. Roads may be temporarily or permanently closed for various reasons (e. g. utility engineering work, pedestrianisation, new narrow layout). Supply chains for critical components of the track which rely on a small number of sources and local access.

	Fuel supply system	Most track maintenance machines (such as measurement trains, tamping machines) are powered by diesel engines and hence need fuel. In the long-time scale, the fuel supply is dependent on the supply chain security of the fuel (e.g. future oil crisis).
	Natural environment	The natural environment can cause major and minor disruptions to a track system. Examples of such disruptions include invasive weed species, the presence of protected species in construction or maintenance sites, rapid or slow changes in geological features such as landslides, and features such as landslides, leaf fall, and pests on the track.

Table 4 The identified flows/linkages between the civil engineering infrastructure subsystems and external systems (source: RSSB, 2016)

		Civil engineering infrastructure
External systems	Electrical power system	Train stations, train depots, drainage systems and tunnels are highly reliant on electrical power in terms of operation, maintenance and construction. There are railway-owned power supply systems for some facilities/equipment, however other facilities/equipment receive power directly from a local electricity-supply network. Lighting (e.g. lighting systems in tunnels), air conditioners and maintenance/construction machinery are examples of electrical power consumers.
	Water-related system	Disruption in external water mains and flood defence systems can cause flooding of infrastructure and their assets. Blockage of drainage (downstream water pathways) can also lead to flooding in railway premises. Water mains and rivers can potentially act as pathways to transfer external risks (such as chemical pollutants) to bridges, tunnels, stations and other infrastructure. This can not only cause flooding around the formation of the track but also affect the durability and stability of the infrastructure and interrupt maintenance practices. Underground tunnels in urban areas are mainly vulnerable to flooding caused by burst water mains. Changes in ground water systems can create a large impact on the stability of infrastructures. Tidal effects can increase the erosion effect in coastal infrastructure.

	Transport system	Access to offices and sites depends on the local roads and public transportation. Entry routes (e. g. local roads) for machinery may be limited. Roads may be temporarily or permanently closed for various reasons (e. g. utility engineering work, pedestrianisation, and new narrow layout).
	Fuel supply system	N/A
	Natural environment	The natural environment can cause major and minor disruption to infrastructure during operation and maintenance. Examples include the presence of invasive vegetation and chloride attack on concrete structures. Also, the impact of wave energy on coastal railways is destructive.

Table 5 The identified flows/linkages between the signalling and control subsystems and external systems (source: RSSB, 2016)

		Signalling and control system
External systems	Electrical power system	Most of the critical signalling and control system assets use electrical power for operation, such as interlocking, signal gantries and communication and control centres.
	Water-related system	Burst water mains, malfunctions of external drainage and defects in flood defence systems can cause flooding of signalling and control system assets. The assets to be considered should not be limited to railway-owned ones but include ones owned by external organisations/companies (e.g. mobile-phone base stations). A water supply shortage could incapacitate key operation facilities (e.g. control centres) because of breaching health and safety standards.
	Transport system	Public transport disruption and local road closures can affect the access of key personnel (e. g. signallers at control centres). Supply chains of control system software (companies may go out of business).
	Fuel supply system	Key facilities (e.g. control centres) have diesel electricity-generators. Because a multiple energy shortage can happen during a major incident, it would be necessary to ensure fuel is supplied to backup systems during major incidents.

	Natural environment	Vegetation can be disruptive to signalling assets and could cause, for example, track circuit failure and invisibility of signal aspects. Tree roots may destabilise the bases of key line-side equipment.

Table 6 The identified flows/linkages between the electrical power supply subsystem and external systems (source: RSSB, 2016)

		Electrical power supply
External systems	Electrical power system	The National Grid provides electrical power to railway power substations which is then distributed to railway facilities through a variety of means, including cables, wires and third rails.
	Water-related system	Disruption in external water mains, drainage and flood defence systems can cause flooding of electrical power assets. The assets to be considered should not be limited to railway-owned ones but should include key facilities owned by electricity providers.
	Transport system	Public transport disruption and local road closures can affect the access of key personnel.
	Fuel supply system	N/A
	Natural environment	Uncontrolled vegetation can be disruptive to power assets. For example, falling trees may dislodge overhead line equipment.

Table 7 The identified flows/linkages between the rolling stock subsystem and external systems (source: RSSB, 2016)

		Rolling stock
External systems	Electrical power system	Electrified rolling stock uses electricity for traction, door functioning, lighting, air conditioning, etc. The power transmits either through overhead wires and pantographs or third rails and collector shoes.
	Water-related system	Disruption in external water mains and flood defence systems can cause flooding of rolling stock depots and other assets. Water supply shortage or sewage problems may affect the operations of depots (e.g. water jetting for autumn leaves as well as water for worker offices) and trains (e.g. water for toilets).
	Transport system	Public transport disruption and local road closures can affect the access of passengers as well as key personnel (drivers, depot personnel) to passenger and freight trains.
	Fuel supply system	The operation of non-electrified lines depends on the fuel supply chain and its security.
	Natural environment	Leaf contamination and other natural contaminations including coal dust and oil can significantly impact the adhesion quality (traction and braking).

Although the above lists are not comprehensive and are mainly focused on the concerns of industrial practitioners in the UK, they provide a valuable and new insight for the qualitative literature of infrastructure interdependencies for railways at an operational environment with a scenario-based perspective.

In addition to the identification of dependencies as presented above, RSSB (2016) has also made recommendations for different sectors for future decision making and investment. Although such recommendations on their own cannot further describe the existing interdependencies for the railway sector, they can help in acknowledging the criticality of the interdependencies. These recommendations are also useful in terms of indicating the requirements of further academic research in relevant fields. According to RSSB (2016), interviews with industrial experts confirmed that many elements of the railway system rely on electrical power systems. Therefore, in terms of disruption to normal operation, it would be necessary to locate the key electrical facilities that are critical for railway operations and examine how electricity is supplied to them at local and regional scale. For instance, in Port of Dover, an electricity transformer for railways which is located below ground level was nearly flooded in a storm surge, which could have severely disrupted its operation. Moreover, it is suggested that the external electricity supplies that are linked to key railway facilities need to be identified and investigated through collaboration with the electricity suppliers. Although these electricity supplies are not owned/managed by the railway companies, the impact of their failure on railway operations is paramount and the railway's stakeholders should have a great interest in this issue (RSSB, 2016).

In addition, regarding the reliance of the electrical power generators on the railway for transporting commodities such as coal and biomass from ports to plants, it is recommended to set up a forum between the rail and electricity (generation and supply) industries to cultivate a better understanding of interdependencies between them. Such an understanding can be used to improve the resilience of each industry (RSSB, 2016).

On the other hand, whereas the dependency on electrical power supply may be obvious, the dependency on water-related systems has not attracted attention but is nevertheless important. In the short-time scale, burst water mains or problems with sewers or drainage could bring water into railway premises and cause flooding. This risk is significant at inner city tunnel sections and indeed investigations have shown that London Underground has identified burst water mains as one of the potential causes of flood. In addition, railway drainage systems often rely on other drainage or sewer systems for distribution, and disruption in downstream systems could cause problems. Moreover, in the long-time scale, changes in ground water level/

movements, which may be caused by changes in precipitation patterns (due to climate change), or construction of geotechnical structures near the railway line could impose serious risks to the railway system. The railway industry should consider water systems (i.e. water mains, external drainage system) as potential causes of flooding in railway premises. In urban areas, water from burst water mains could flood railway underground tunnels and stop railway operations. It is recommended that the railway industry should work together with water companies to identify their water mains and key drainage systems whose failure could affect railway operations and seek appropriate risk alleviation measures. It is also recommended that the railway asset management system should include and consider the nearby water mains, sewers and external drainage systems. Effective drainage solutions also need to be employed for areas with high likelihood of landslips in order to prevent them. Moreover, ground water needs to be considered as a potential risk to the railway system and its operations. Although changes in the ground water level and movements may be subtle in a short period of time, if changes were to build up, they would affect the stability of geotechnical structures and cause landslips. It is suggested that the ground water level and movements around key geotechnical structures be monitored (RSSB, 2016).

Once geotechnical structures fail, it would take a very long time to reconstruct/repair them and thus the impact of a failure could be enormous. Hence, more attention should be paid to this potential risk. On the other hand, access transport systems (i.e. public transport systems and road networks which ensure flows of people and resources to/from the railway system) play an important role by providing the means of commuting for key railway personnel as well as for passengers. Whilst commuting is the responsibility of each individual member of staff, it is necessary to have a system in place whereby key operational personnel can arrive at the depots regardless of the conditions of access transport systems. Although each operational department might have a contingency plan, there should also be a cross-department mechanism that integrates different plans and is usedin the case of a minimum turn-out in each department. For example, a contingency timetable can be created based on not only the desired service frequency but also the possible and required rates of attendance of key staff across the railway system including drivers, station staff and signal controllers (RSSB, 2016). It can be argued that most of the above recommendations were solely made based on engaging with selected subject matter experts across several regions and therefore the scope of the study (as a national-level research) was rather limited. Indeed, the concerns of stakeholders involved in the process of extracting dependencies and providing recommendations largely influenced the outcome of the study.

The above literature showed that although, at an infrastructure level, some of the dependencies have been frequently explained qualitatively, there are very few studies which attempted to investigate dependencies and explain them at a sector level (e.g. railway and water supply). To summarise, a conceptual and qualitative perspective of infrastructure interdependencies could be essential as the initial step towards other investigations with different purposes such as predicting the desired or unwanted output as explained in the next sections.

2.1.2 Economic perspective

The second viewpoint of the interdependency-related research considers national security/protection, wellbeing and economic prosperity as major concerns of the investigation of interdependencies. In this case, the importance of infrastructure interdependencies has been assessed regarding the proper functioning of an economy and society and to prioritise vulnerabilities at a national scale. These studies develop or employ different methods and models including macroscopic input-output models that act as a framework to study the equilibrium of an economy at a national or regional scale (Haimes and Jiang, 2001, Haimes et al., 2005, Lian and Haimes, 2006, Santos, 2006, Hallegatte, 2008 and Chen et al., 2009). Furthermore, economic-based research also employed agent-based models (e.g. Barton et al., 2000, and Barton and Stamber, 2000, Brown et al., 2004, Oliva et al., 2010), Petri-net based models (e.g. Gursesli and Desrochers, 2003), system dynamics as well as network models (e.g. Apostolakis and Lemon, 2005, Min et al., 2007, Svendsen and Wolthusen, 2007, Zio and Sansavini, 2011 and Trucco et al., 2012). Some of these approaches are explained later in section 2.2 where required. Note that the outcome of economic-based studies could mainly be a tool/model which enables a better or more comprehensive understanding of the interconnectedness between complex infrastructure systems and the effect of changes in one system on another.

Primarily, an input-output based economic model as the foundation of an interindustry analysis offers a way to trace resources and products within an economy by purchases. The Leontief model, developed by Wassily Leontief in the 1930's, which is one of the most widely applied methods in economics, could define the interconnectedness or interdependencies among the various sectors of an economy and forecasts how a change in one sector will affect the others. The model is usually constructed from observed economic data for a specific geographical scale (international, national, state, regional etc) or the area in which produced goods are assumed as the output and the consumed goods are assumed as the input. The Leontief model assumes a disruption in demand for a specific sector and traces the impacts upstream in the supply chain demand-driven propagation (Chen et al., 2009 and Miller and Blair, 2009). The commodity or service flow throughout the economic sectors in a Leontief model represents the physical interconnections among these infrastructure sectors. Later, several extensions to this basic framework were developed such as Ghosh models which determine the supply-driven interdependencies (for more information refer to Chen et al., 2009). Santos and Haimes introduced the concept of "inoperability" which is equivalent to the incapability of a system to perform its designed functions (e.g. the extent to which a transport system can supply a required amount of goods to its customers at a scheduled time) (Santos and Haimes, 2004). Haimes found that a model like the original Leontief economic model could be used to assess the risk of inoperability (in monetary terms) caused by malicious attacks (Chen et al., 2009).

Usually, the result of economic-based interdependency analysis is a set of coefficients that indicate how much of a given sector's output is demanded by each economic sector per dollar output downstream from the given sector in normal and disrupted/changed condition. For example, a significant reduction in demand for truck transportation will in turn reduce demand in the oil and gas extraction sector as well as the pipeline transportation sector which delivers the fuels. This inoperability could be the implication of a change in consumer behaviour or external events such as natural disasters. Chen et al., 2009 used economic input-output analysis to estimate a broad class of critical infrastructure interdependencies including normal disruptions and natural hazards. However, it is argued that input-output analysis are rather limited because of basic assumption of constancy of input co-efficient of production and linear equations and hence inter-industry connections are not examined dynamically in an economy.

Regarding the rail-related interdependencies, the study stated that producing $1 million of service in the rail transportation industry requires only $700 of electric power directly. Most likely this figure is obvious for industrial practitioners. However, in fact the total supply chain dependence between the rail transportation sector and the power generation sector is equal to $7,500 per $1 million of service, which is more than 10 times the direct dependence. This larger total requirement is caused by $3,000 of "second level upstream" electricity purchases and $1,900 of "third-level upstream" purchases. In Figure 11, Chen et al. (2009) developed a so-called "Nth order graph" (based on Leontief-based results) to show more realistically the dependence of the rail transportation industry on the power generation and supply sector across various levels of the supply chain. This result suggests that a great deal of indirect dependencies is invisible in addition to their obvious direct linkage. Such hidden dependencies are formed by the involvement of many intermediate sectors. Chen et al. (2009) argued that managers of rail transportation infrastructure are possibly not aware of these indirect dependencies, and their relative magnitude.

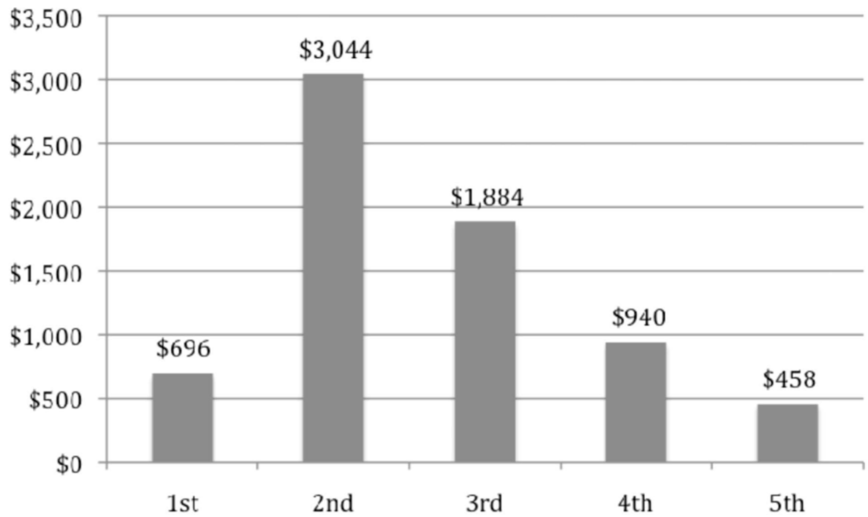


Figure 11 Nth Order graph of rail transportation's dependence on power generation and supply per $1 million rail transportation output (Leontief-based results) (source: Chen et al., 2009, figure 4.)

It is notable that with regard to the current literature of infrastructure interdependencies which focused on inoperability and economic prosperity, the scale remained mainly at the output of an infrastructure/sector. This is primarily because the nature of the macroscopic input-output models which are the fundamental of economic-based studies for infrastructure interdependencies cannot capture connections at a high resolution.

On the other hand, using a rather non-conventional approach, a recent study about the interdependencies of the HS2 (High Speed 2) project in the UK attempted to show the significance of a new railway project (at planning and construction phase) for the prosperity of other infrastructure systems by a qualitative and workshop-based approach (Rosenberg and Carhart, 2014). The study conceptually investigated the benefits that HS2 could potentially bring for ICT, energy, water and transport infrastructures. For example, the HS2 Phase 2 route can potentially provide an added corridor for the ICT access network, to improve links from subscribers to their service provider. Nevertheless, this indicates how, at a sub-sector level, infrastructure interdependencies exist for the railway transportation and they could be further investigated. This study remained at an identification level of interdependencies (i.e. quite conceptually) between the railway route and other infrastructure systems with a focus on economic prosperity, without any evaluation and further validation of such identified dependencies. It is argued that the study could not produce a complete list of all potential interdependencies because of the limitations imposed by the workshop conditions (e.g. time limits, concerns etc.). Also, it is not possible to conclude that the interdependencies found here are of the highest critical importance (i.e. measured by economic value) as the evaluation is limited to qualitative assessment only.

Note that the economic-based studies can support the development of new theories and models that help system/infrastructures determine the required adjustments for achieving a new production level or economic efficiency. They can eventually support the development of generic national-scale risk models for complex interdependent systems and to predict infrastructure responses. To summarise, the economic-based theory studies offer a useful understanding of operability and inoperability of infrastructure dependencies and analyse the propagation of perturbation among interconnected infrastructures.

2.1.3 Vulnerability perspective

It should be noted that the dependencies that exist between infrastructures can be both an advantage to economic prosperity and a vulnerability to magnify the impact of infrastructure failures (for example through cascades). CST (2009) argued that there is a lack of understanding of the vulnerabilities or fragility of infrastructure systems especially in the case of potential cross-sectoral risks. Unless addressed, such dependencies can lead to a misdirected level of dependence on other systems that could also have serious consequences. The vulnerability of infrastructure systems has been clearly demonstrated through events such as the Northeast blackout in the USA and Canada in 2003 and by major rail transport disruptions during prolonged flooding in England over the winter of 2013/2014 (Hall et al., 2016). Thus, there needs to be a robust analysis of these interconnections especially within the context of the vulnerability to failure in order to facilitate a more pro-active approach to managing the interdependencies and risks.

Therefore, the third viewpoint within the existing literature and its research focus considers risks, the failures of interdependent infrastructures and how to facilitate resilience to future challenges. Such studies vary from an economic/social and national scale (e.g. Haimes and Jiang, 2001, Chang et al., 2007, Luiijf et al., 2008, Van Eeten et al., 2011, Wang et al., 2012, Kotzanikolaou et al., 2013, Wang et al., 2013, , Kelly, 2015, Pant et al., 2018) to a more technical and/or regional scale (e.g. Johansson et al., 2007, Jönsson et al., 2008, Johansson, 2010, Johansson and Hassel, 2010, Utne et al., 2011, Johansson et al., 2013, Jaroszweski et al., 2014, Jaroszweski et al., 2015 and Binti Sa'adin et al., 2016). A range of approaches have been used in these studies including conceptual frameworks, empirical investigation and network-based models. Note that the type of failures due to interdependent infrastructures systems may vary, including common cause, cascading and escalating (Rinaldi et al., 2001). This has been clarified and explained in Chapter 1.

For instance, Luiijf et al. (2008) empirically studied cascading effects caused by (inter)dependencies across different infrastructures including energy, transport, water and telecommunications using a database of 2,375 serious incidents all over the world as reported by news media. Only events which had a noticeable effect on society are recorded, for instance, when at least 10,000 electric power customers were affected. This clearly indicates an example of how criticality for interdependency-related research is defined and what is assumed to be important for the scope of each study, while the rest remains outside such scope. The study investigated in which infrastructure system an event originates and which infrastructures are affected consequently (refer to Figure 12 for an example of the results). In cases where the events have not been recognised as cascade-related, the term “no sector” has been used. In such disruptions, the initiating events resulted either from a large range of external factors (e.g., weather, deliberate human actions, and economical factors) or internal factors (e.g., human error, technical failure) and in some cases a combination of both. The dependency matrix in Figure 12 shows that energy and telecommunications are the main infrastructure systems/sectors that initiate cascades. Energy is the only system which initiates a greater number of cascades than it receives. Neglecting the non-cascade-initiated events, the empirical results showed that the dependency matrix is not densely populated and that cascades are highly asymmetrical (Figure 12). The energy and telecommunication sectors cause outages in other sectors (60% and 24% respectively), but not many other sectors cause outages in energy, telecommunication and internet. The percentage of events in affected energy, telecommunication and internet,(15%, 25% and 10% respectively) are largely caused by services within these three sectors. To summarise, the dependencies appear highly focused and directional and therefore this data suggests that a reciprocal relationship cannot be occurring frequently. This may suggest that while (inter)dependencies are at least theoretically and conceptually identified everywhere, the available data is rarely strong enough for or/and capable of indicating a secondary outage, as is reported by the news media. It raises issues such as whether interdependencies may only occur after a longer period of disruption or whether the cascading outage events are so invisible in the chaos caused by the primary outage and its effects that the media do not cover them.

Sector	Initiating sector											
	No sector	Energy	Financial Services	Government	Health	Industry	Internet	Postal	Telecom	Transport	Water	Grand Total
Education	1	1									2	4
Energy	515	65				4			2	1	3	589
Financial Services	34	5	3				3		15			60
Food	4	3								1		8
Government	27	17		1	1	1	4		14	1	1	67
Health	23	11			2				2		1	39
Industry	12	12				1				1	1	27
Internet	109	14					10		27			160
Postal Services	1											1
Telecom	170	62					1		57	5		295
Transport	294	98		1		3		1	5	15	5	422
Water	58	14				2					2	76
Total	1248	302	3	2	3	11	18	1	122	24	15	1749

Figure 12 Events categorised by initiating sector and affected sector (infrastructure systems) by the number of events (source: Luiijf et al., 2008, table 2.)

Luiijf et al., 2008 concluded that most cascading failures originated in the energy and telecommunication sectors. Their research also suspected that critical infrastructure (inter)dependencies occur at a technical environment which is not visible to incident reports. Once more, this emphasizes the importance of investigating infrastructure interdependencies at a technical and detailed level. It is argued that cascading effects due to interdependencies are hardly ever reported and are usually hidden in reports about emergency responses to incidents. This may result in only incomplete and limited empirical data about failures being available. However, investigating such data may still be helpful for interdependency-related risk prioritisation and decision making. It is argued that the study by Luiijf et al., 2008 could be biased by the limited set of European languages used and reporting practices. Moreover, it is argued that investigating empirical data may function as a complementary approach to the conceptual approach towards dependency analysis (conducted by e.g. Rinaldi et al., 2001 and Rinaldi, 2004), which is not necessarily based on real-life data or a full analysis of the past incidents.

In a different example, on a national scale, Thacker et al., 2017, proposed a metric of infrastructure criticality in terms of the number of users that may be disrupted (directly and indirectly) by the failure of physically interdependent infrastructures. 200,000 failure scenarios were tested using the national scale data of energy, transport, waste and communication sectors in England and Wales. Using Kernel density estimation as a statistical tool, the study identified statistically significant infrastructure criticality hotspots. The results showed that hotspots are usually around the border of urban areas where large facilities upon which many users depend are focussed. As for railway systems, there is a lack of similar empirical investigations of disruptions due to external initiating events which are not even clearly known yet within the academic literature. This could be potentially an interesting area for future investigations, although it may require a significant effort in terms of data collection and analysis.

However, adopting a different viewpoint while using a more predictive approach within a technical and national scope, Pant et al. (2015) investigated the relative criticality of different nodes and edges (or links) on the network of the passenger traffic of GB railways. The study conducted the analysis within the context of vulnerability to two cases of the external risks, namely flooding and failure of the power supply using network-based modelling. Since the study was supposed to lead towards better risk management and resilience investment decisions, the aim here has been defined as to identify the relative criticality of the network elements which different risk events are likely to affect. The study has demonstrated how the measure of infrastructure criticality allows the identification of the most vulnerable nodes (i.e. stations and junctions in this case) and links (i.e. tracks in this case) in a railway network to a range of risks. Here, the main metric of interest (the relative criticality of the railway network) has been defined based on the passenger traffic they carry and several other factors. The study noted that the only determinant of aggregate disruption is not the volume of traffic on a specific route. "In a dense railway network where diversionary routes are available, the loss of a specific link will have a much smaller impact than it would if that edge formed a bottleneck between two large traffic generators/attractors" (Pant et al., 2015). This clearly indicates the importance and the complexity of the criticality metric in interdependency-related risk analyses. The study highlighted the major routes and stations with high risks of flooding and hence more vulnerable to flood risk. The study in fact focused only on a limited number of components/properties of systems of interest which seemed to be critical regarding the dependency scenario.

Figure 13(a) shows the distribution of the passenger trips (shown as fractions of the total network trips) through the nodes and their related edges. Compared with some other results of the study, it is evident that some of the very high flow network routes are at risk of flooding. On the other hand, Figure 13(b) shows the energy supply system that provides traction electricity for specific routes. The system includes 125 substations (expressed as nodes in the inset of the figure). The figure demonstrates the result of multiple passenger trip disruption if certain fractions of the traction substations fail (considered as nodes which are removed), thus cutting off the electricity supply to the rail network. Most of the traction systems are located along routes where most of the passenger flows exist, which results in almost 90% of trips lost if the entire electric traction system shuts down. Pant et al. (2015) concluded that a similar methodology (using network theory to find vulnerability) could be used to develop tools to cover all risk categories (internal and external) and therefore help assessing where investment in increased resilience should be focused. It could also help to identify which categories of risk have the greatest overall impact on railway network vulnerability, and this may in turn have implications for policy in related areas. It should be noted that the risks (and therefore the criticality levels) identified here will not remain constant over time as systems (both internal and external) evolve.

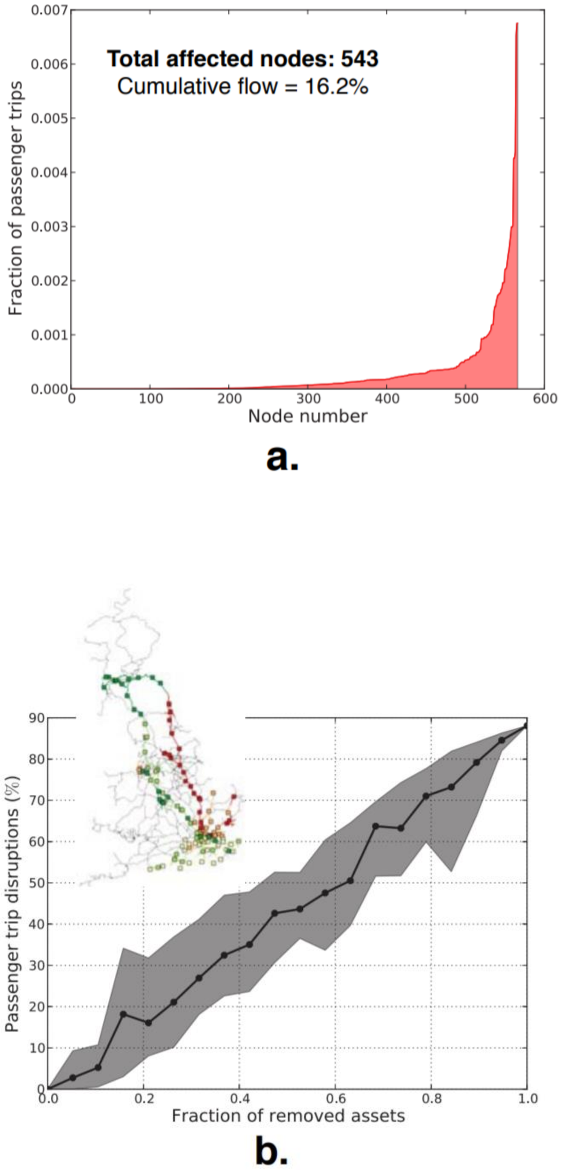


Figure 13(a) The distribution of the passenger trips at risk due to nodes (and corresponding edges) that are vulnerable to 1 in 1000 year flood event, and (b) Vulnerability of the overall rail network due to traction system (shown in the inset figure) failures (source: Pant et al., 2015, figure 2.)

Similarly, Pant et al. (2016) presented a mathematical formulation of the vulnerability assessment as well as some network models, which include the geographic, physical and operational characteristics of connecting nodes and edges of GB railway and the interdependent external infrastructures. The methodology was later used to assess links between GB railway's critical assets and external infrastructures that support railway operations. The study quantified the negative consequences of disruptions for passenger travel resulting from failed stations, junctions or track sections in the railway network due to dependency on other infrastructure systems. For instance, Figure 14 shows the vulnerability assessment results when random failures are introduced in the railway infrastructure network. The results are generated following 250 simulation runs per failure magnitude and showed that railway infrastructure is most vulnerable to external infrastructure failures in the following order (high to low): (i) electricity, (ii) telecommunications (ICT), (iii) water, (iv) natural gas, and (v) liquid/solid fuels.

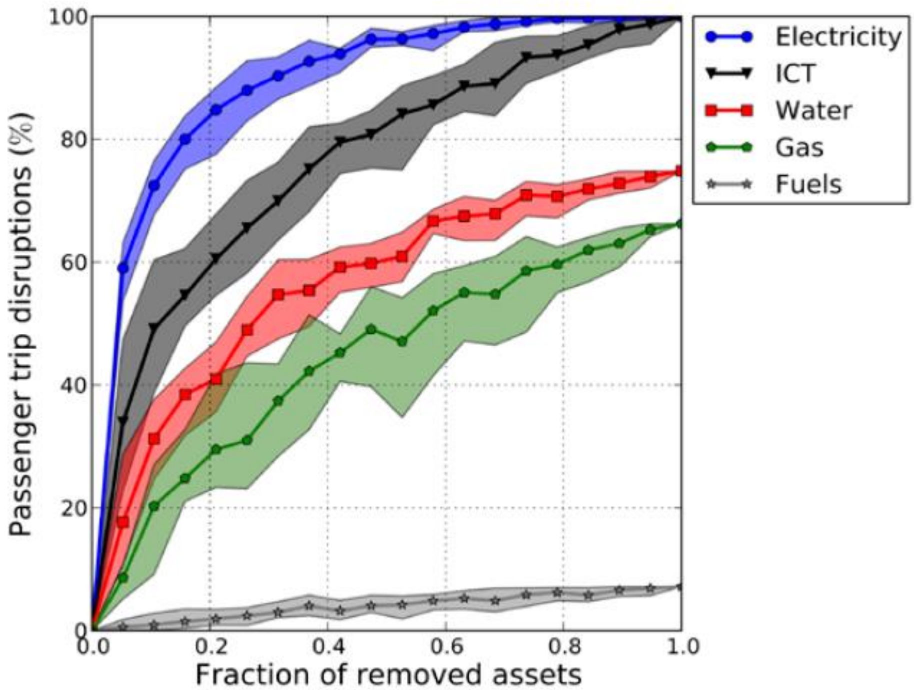


Figure 14 Vulnerability of the railway network due to failures induced through other infrastructures (Source: Pant et al., 2016, figure 7.)

Overall, Pant et al., 2016 generated a highly relevant quantitative vulnerability analysis for the Great Britain railway network, which could enable identification of the most severe failure scenarios and spatial impacts.

Johansson and Hassel (2010) investigated the interdependency of a railway system as a "system of systems" on external power supply systems in the context of vulnerability analysis. The term 'risk' has been described as "the combination of probability and severity of adverse effects", while, 'vulnerability' has been defined as "a global system property that expresses the extent of adverse effects caused by the occurrence of a specific hazardous event" (Johansson and Hassel, 2010). The study assumed that dependency as a unidirectional relationship can exist in the micro-level systems (in addition to the macro-level system as defined by Rinaldi et al., 2001). This means that the state of a component of a system depends on the state of a component in another system. Moreover, to study both physical and functional properties of infrastructure systems and to evaluate the performance of each system, the network model together with the functional model, the geographical/spatial attributes of the systems dependency functions between systems have been considered as the main elements for this modelling approach. The modelling approach has been applied to an imaginary electrified railway, resembling the actual railway system in southern Sweden in terms of structural, functional and geographical attributes. "The operation of the railway system has first- and second-order dependencies to four other infrastructures, namely: the traction power system, the telecommunication system, the auxiliary power system and finally the electrical in-feed system" (Johansson and Hassel, 2010). The research focused on the vulnerability analysis in terms of the impact of technical interdependencies in the timespan of up to 24 hours (i.e. short time scale). Figure 15 presents the results from 1000 simulations which show the average consequences in the railway system when each of the four other systems are separately disrupted as well as when disruption scenarios occurred to all four systems simultaneously. The shape of the curves changes significantly depending on the disrupted system. Here, the negative consequence for the railway system has been calculated by summing the loss of service (expressed as the fraction of customers who cannot reach their desired destination) over all time steps. This provides a metric that can be interpreted as lost service hours. For example, if the loss of service is 1 for 2 hours the total consequence will be the same as if the loss of service is 0.5 for 4 hours, i.e. 2. As Figure 15 shows, no consequence was observed for the railway system for any magnitude of disruption to the auxiliary power system. This is because "the telecommunication system, which the railway system is dependent on, has redundant power supply and is supplied from the electrical in-feed system" (Johansson and Hassel, 2010). The other curves reach a maximum meeting the requirements of the longest repair time for a component in the disrupted infrastructure. This is because no travellers can reach their destination when all components have been removed. In general, different magnitudes of disruptions for the different systems give very different consequences for the railway system. Such results clearly show the criticality level of the external systems that the railway system depends on.

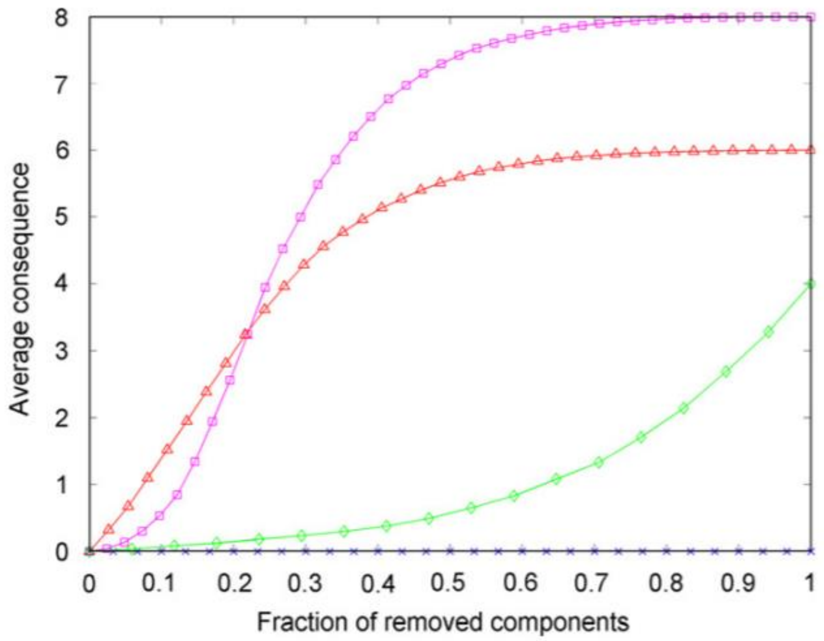


Figure 15 Consequences for the railway system for varying magnitude of the disruption when applied to the traction power system (☐), the telecommunication system (△), the auxiliary power system (x) and the in-feed system (◊) are exposed to random removals. The consequences are averaged for 1000 simulations (source: Johansson and Hassel, 2010, figure 4.)

In a random removal (Figure 15), each component in the system that is exposed to strain has an equal probability of being removed. The study additionally investigated other types of vulnerability, namely critical components vulnerability and critical geographic locations vulnerability, using the same modelling approach. The benefit of this systematic and comprehensive modelling is the ability to account for functional and geographical dependencies and to capture higher-order (more indirect) dependencies. This study concluded that using the above-mentioned modelling approach for a vulnerability analysis of technical infrastructures, such as railways, is promising and suitable. In general, it is argued that because of the constantly evolving nature of complex infrastructure systems, structural and dynamic complexities and interconnection diversity, it is challenging to investigate various vulnerabilities across different infrastructures. Although the above-mentioned studies are usually beneficial to examine the criticality of a highly complex network, the presented results demonstrate little information regarding the dynamics of inter-related systems in detail.

The above section attempted to cover a range of different infrastructure interdependency research studies which focused on the vulnerability and risk perspective of different scales and scopes. Although the scope of studies is not limited to the ones mentioned above, this section provided some useful examples, especially where railways and transport were the infrastructure of interest.

2.1.4 Data management perspective

Taking a different viewpoint, some research focused more on developing new national-scale tools to provide a reliable spatial and temporal database which can support data management. This viewpoint is motivated by the challenge of managing the complexity of critical infrastructure systems, such as the significant amount of data that complex adaptive systems deal with. Big data management approaches and database systems play a critical role in improving the analysis of dependencies between infrastructure systems (Barr et al., 2013, Otto et al., 2016 and Pant et al., 2018). This can pave the way for robust national infrastructure planning and assist the research on both economic prosperity and failure of interdependent infrastructures. Good quality data and information is the key for developing long-term, robust and economically sustainable infrastructure investment plans. It is also evident to infrastructure operators that developing data and information management approaches facilitates better planning and implementation as well as decision making and investment in complex infrastructure systems. Additionally, it is extensively argued that detailed information and understanding of the (inter)dependencies that exist between systems can significantly contribute to a better understanding of how an infrastructure system or sector is performing (Hall et al., 2016). This motivated a number of large-scale research initiatives namely: the U.S. National Research Council report on Sustainable Critical Infrastructure Systems, the Dutch programmes on Next Generation Infrastructure and Knowledge for Climate, the Australian Critical Infrastructure Protection Modelling and Analysis (CIPMA) programme and the U.K.

Infrastructure Transitions Research Consortium (ITRC). These initiatives mainly developed the new suite of infrastructure analysis and modelling tools required to provide a holistic system-of-systems understanding of critical infrastructure. Within such initiatives, and more generally among researchers and practitioners, it has been recognised that the ability to collate, integrate and manage a wide range of diverse infrastructure data at a range of spatial scales and measurement granularity in a cohesive and logical manner is a key requirement. However, it is stated that the development of data management systems explicitly designed for and able to handle the wide range of disparate data and relationships is still at a very early stage (Hall et al., 2016). It is argued that to provide key insights for long-term critical infrastructure planning, tools need to be available which allow the investigation of large numbers of vulnerabilities, demand and interdependencies issues of infrastructure systems.

Barr et al. (2013) and Hall et al. (2016) have described the structure of the UK national scale spatial database framework and analysis system for infrastructures called NISMOD (which is a part of the ITRC initiative). This database allows the analysis of large-scale data and information on infrastructure systems and supports the modelling of the long-term capacity/demand requirements of infrastructures and network risks. This tool, as the UK's first national infrastructure system-of-systems modelling platform and database, could address the challenge of fulfilling the need for suitable data management analysis, modelling and visualization. To develop and manage the database, a combination of relational modelling, network modelling, suites of processing scripts and visualisation engines have been used. The database was developed to collate, manage and provide infrastructure data for the entire UK across the different hierarchical levels/scales (e.g. system of systems, infrastructure systems and sectors, assets) ranging from complete geospatial inventories of assets within a specific infrastructure network, through to aggregated metrics affecting the performance of multiple interdependent infrastructure sectors (Hall et al., 2016). So far NISMOD-DB has been primarily used to support the data management requirements of a suite of infrastructure models ranging from interdependent infrastructure network risk analysis (NISMOD-RV) through to high-level long-term capacity demand modelling between multiple infrastructure sectors (NISMOD-LP). According to Hall et al. (2016) and Barr et al. (2013), NISMOD-DB has been designed and implemented in a modular manner and thus comprises a suite of database management modules which constitute the overall database management system.

Since one of the objectives of the ITRC project is collating complete national-scale representations of infrastructure systems, NISMOD-DB could represent the spatial (geographic) characteristics of infrastructure systems together with their non-spatial characteristics. To achieve this, PostgreSQL a relational database management system (RDBMS), as well as its spatial extension PostGIS have been employed. "PostGIS allows spatial data layers in the form of geometry tables to be encoded and provides a wide range of spatial operators and functions that can be used to process, analyse and manipulate the spatial infrastructure systems layers" (Barr et al., 2013). Furthermore, in the database, tables are categorised based on their use within ITRC and then in terms of the infrastructure system. In the case of the long-term capacity/demand modelling of NISMOD-LP, standard relational tables which show the required inputs and results of the modelling are stored by economic, population (demographic), energy, water (clean and waste), transport and solid waste sectors. Data for the infrastructure risk and vulnerability modelling (NISMOD-RV) is largely stored as PostGIS spatial geometry tables (point, polylines, polygons) representing the location and spatial extent of individual infrastructure system features. Again, these are organised and grouped by infrastructure system; namely, spatial hazards, energy (electric transmission/distribution, gas transmission/distribution), water (supply and waste), transport (road, rail, air, sea (ports)) and solid waste. A full description of the modules as well as database system requirement have been presented by Hall et al. (2016).

As for the application and relevance of such database for this research, the studies which depend on data management systems as a tool for investigating infrastructure interdependencies typically employ a combination of system modelling, data analysis and other methodologies to evaluate a variety of interdependency-related scenarios. For one example of the application of the developed tool within ITRC, the interdependency of the London Underground tube network on electricity transmission was analysed using several cascading dependency failure modes (Figure 16 and Figure 17). In the model, the failure of a substation results in the failure of a dependent tube station along with its associated track. The effect of three types of electricity substation failure, namely: random, ranked by betweenness centrality and ranked by the degree of the number of failed tube stations (the dependency metric) has been studied. It has been concluded that London Underground is primarily vulnerable to the failure of highly connected electricity sub-stations, because failure based on high degree and high betweenness showed comparatively more impact on the operation of the tube network than other types of failure.

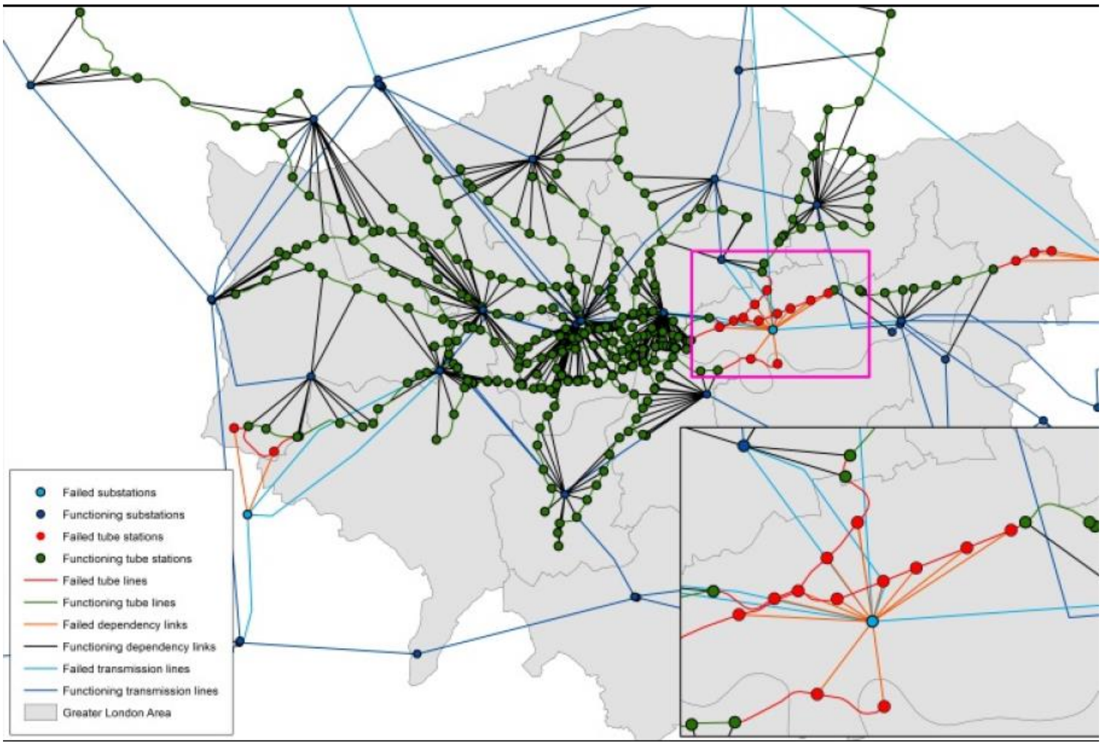


Figure 16 tube (London Underground) stations, power substations and railway lines as an interdependent network of nodes and edges (source: Barr et al., 2013, figure 6.)

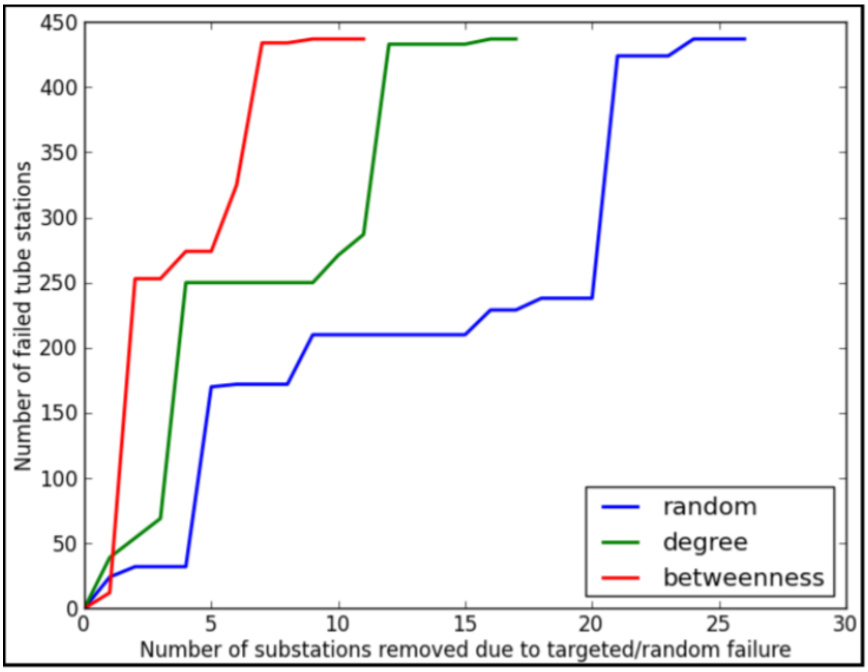


Figure 17 The result of three different types of failures at substations and its effect on underground stations (source: Barr et al., 2013, figure 6.)

As a non-railway example for the other ITRC consortium projects, NISMOD-DB++ as an extension of NISMOD-DB was developed to allow analysis and modelling at the intra-urban level of infrastructure assets and buildings by employing a federated database architecture (a set of cooperating databases) (Robson et al., 2018). Moreover, Lovrić et al. (2017) described a multi-modal multi-scale national transport model which is developed by ITRC consisting of passenger and freight transport via highways, railways, airports, seaports and local transit networks. The model forecasts future demand for different modes on individual flows employing an elasticity-based simulation approach. These flows are then assigned to transport networks to measure infrastructure capacity utilisation and find new estimates of inter-zonal travel times. "The model considered cross-sectoral interdependencies with other infrastructure networks, including the energy sector (where transport is the largest consuming sector), digital communications (which provide bandwidth to passengers and enable smart mobility), waste management (which requires transport services) and water supply (where flooding poses a major risk of transport disruptions)" (Lovrić et al., 2017).

One must note that although research in the field of data management may give similar case study results to the ones mentioned in section 2.1.2 and/or 2.1.3, the main contribution of big data management-focused studies to the science is the development of powerful tools. Such tools can capture and analyse all sorts of dependencies (i.e. as many and diverse as possible, including technical, economic, physical, cyber etc) of all infrastructures at a national scale and hence evaluate dependencies of various examples and case studies at multiple levels.

2.1.5 Summary and discussion

This section classified the existing academic literature of infrastructure interdependency into four main perspectives, namely conceptual, economic, vulnerability/risk-based and data management-based studies. To summarize, conceptual studies mainly characterize the existing infrastructure interdependencies and hence they delineate the framework for other groups of studies. The recent railway-related qualitative studies highlighted several critical little-known interdependency scenarios for further work (e.g. Rosenberg and Carhart, 2014, and RSSB, 2016). Such studies usually employ qualitative metrics to explain interdependencies such as tight versus loose and adaptive versus inflexible to describe the dependency of one sector/infrastructure system on another. Their output can act both as a general guideline for practitioners and infrastructure operators/regulators to prioritise investment and as a framework for researchers to evaluate the conceptual findings. Therefore, qualitative investigation of interdependencies on its own cannot provide a comprehensive decision support tool for one sector where quantified evidence regarding the effect of one sector on another is required.

The economic-based studies, on the other hand, offer a useful understanding of operability and inoperability of infrastructure systems in an economic environment, usually by employing and presenting economic and monetary-based indices such as the dollar flows of goods/services between sectors. Therefore, such studies could indicate how one sector, such as railways, depends on other sectors to operate as well as how perturbation may propagate among interconnected infrastructure in an economic environment only. The nature of economic indices and metrics cannot capture various types of interdependencies that exist across infrastructures such as loss of service (technical) and damage to reputations or change in customer behaviour (social).

On the other hand, vulnerability/risk-based studies usually focus on investigating past events or predicting predefined risk scenarios to understand the propagation of failure among infrastructures. The output/results of this group of studies mainly appears in the form of correlating the failure of critical components of interdependent systems to the disruption of one system of interest (e.g. loss of service, loss of critical assets etc.). Hence, for instance, the metrics focus on showing the effect of failure in the form of the duration of cascading failures, etc. Such studies are very useful in terms of providing a detailed understanding of the effect of one specific risk scenario related to interdependencies. These studies help in detailed vulnerability mapping and finding the most critical assets and the worst-case scenarios for an infrastructure. As for the railway systems, the scenario of vulnerability to failure of power has received relatively more attention compared to many other scenarios (e.g. failure of water, gas and fuels).

Lastly, the efforts towards producing big data management tools facilitate investigation of infrastructure interdependencies at a national scale. These studies can produce similar sorts of output to the economic-based and vulnerability-based studies (based on the requirement of the research) but potentially more comprehensively and reliably.

In general, the review of the literature showed that because critical infrastructures are various, complex, adaptive, nonlinear and dynamic systems, there are many dependencies and interactions still little-known (especially at a technical, sectoral and regional scale). Conceptual knowledge on an abstract level on its own cannot help complex adaptive systems to adapt further complexities such as changes to demand and services. On the other hand, there are many characteristics and dimensions to infrastructure dependency that all require attention for a comprehensive knowledge of the topic. Also, as the natures of infrastructures and hence sectors within them are different, there are greatly different metrics/indices (including economic and risk-related ones) by which dependencies can be quantitatively explained (e.g. the number of users affected by a cascading failure). Indeed, more metrics need to be introduced for other little-known dependencies which have not received enough attention. Furthermore, note that most of the studies which modelled the railway as a network at a national scale simplified the internal assets (at a component-level) of the railway systems and the way they interact with each other and with external interdependent infrastructure systems (i.e. Pant et al., 2015). This indicates that many assumptions are made which affect the results of these studies. It is also important to note that, because the existing literature varies in terms of dimensions (as previously mentioned), the outputs appear in forms of very different metrics. For example, Rinaldi et al. (2001) focused on long-time scale dependencies between different infrastructures and therefore the results appeared in the form of conceptual indices only, whereas shorter term analyses such as studies of the dynamics of the day to day operation of systems and possible disruptions, which need a more quantified and engineering approach, result in output in the form of risk-related or system-engineering indices.

It is important to mention that metrics are essential for quantification of interdependencies and hence for analysing the behaviour of critical infrastructures. Briefly, interdependency metrics can be classified, based on their information content, decision support and risk analysis capabilities, and computational costs (Casalicchio and Galli, 2008), into three groups. The first group of metrics is called shape metrics that quantify macro or shape characteristics of interdependencies, such as direction, and duration of a dependency, such as the ratio of the duration of an outage in one infrastructure and the duration of the outage in another infrastructure where the disruption initiated. Secondly, there are core metrics that measure the causes and effects of outages for specific infrastructure components and the effectiveness of strategies/mechanisms for improving critical infrastructures' protection and resilience. Finally, sector-specific metrics measure the states of infrastructures at the global and component levels regarding the interdependencies with other systems.

Figure 18 shows how core, shape and sector-specific metrics are positioned in the three-dimensional space of decision support capabilities, information content and cost (Casalicchio and Galli, 2008). Based on this classification, it is reasonable to conclude that most economic and national-scale research included shape metrics as they largely ignore details of infrastructures at a component level, while other studies such as those which employ network-based modelling can produce core and sector- specific metrics depending on the aim of the research.

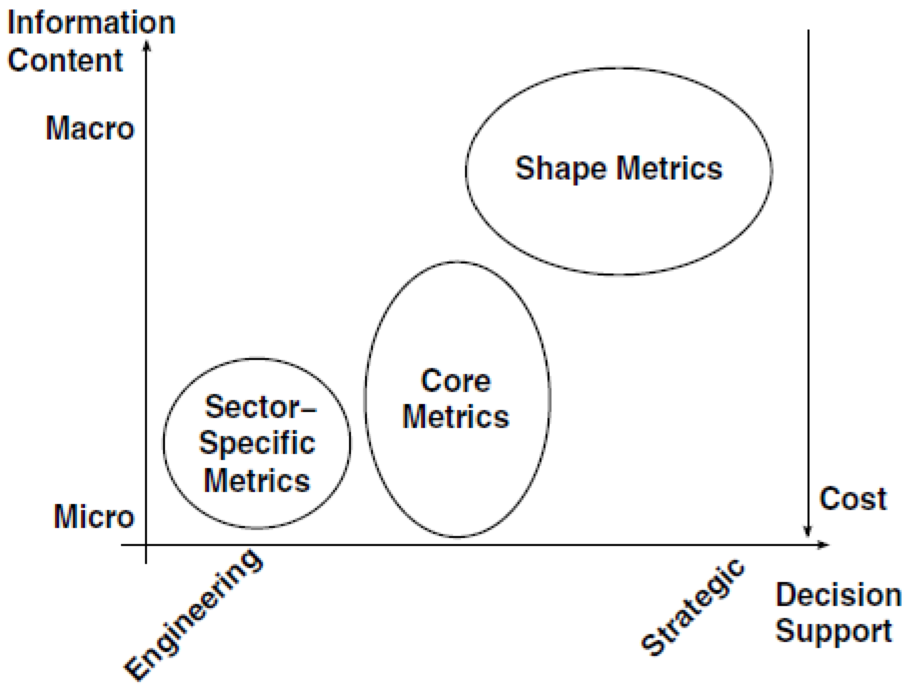


Figure 18 Classification of metrics for quantifying infrastructure interdependencies (source: Casalicchio and Galli, 2008, figure 2.)

The review of literature in this chapter showed that while conceptual studies focused merely on capturing the lower order (direct) interdependencies (Rinaldi et al., 2001, Hall et al., 2014 and Chang et al., 2007), the technical studies focused on a limited number of dependency scenarios which are typically inherent in the systems. Similarly, at a sector level (e.g. railways) there are a limited number of better-known dependency scenarios, such as the ones between railways and power production, which received attention in both normal operating conditions and failure conditions (e.g. scenarios of transporting commodities to power plants and failure of electricity substations which power railways).

At an infrastructure level (e.g. transport, water, power etc.) the resolution and order of dependencies (e.g. higher vs lower) is low. Hence, although at a sector level more technical research is required, at an infrastructure level more resolution and integration with higher order dependency analysis would be useful. Furthermore, there is a lack of suitable and sufficient empirical datasets available for both the normal operation of complex infrastructures and events of their failures to support studying dependencies.

Most existing literature agrees that models and simulation tools can provide considerable insight into the complex nature of infrastructure dependency and its characteristics. Therefore, it would be reasonable to conclude that investigation into the field of infrastructure dependency is still in its early stages. Many dependency scenarios are poorly understood in the literature and even hidden from infrastructure operators.

As for the investigation of interdependencies for railway systems, the range of available studies in each category is rather limited. There is almost no research which theoretically characterised and introduced all interdependencies for complex railway systems which could act as a baseline for further investigation. Also, many interdependencies are hidden in reports without any specific focus on system-level identification of linkages and connections. From an economic perspective, the railway system was ignored in many studies since it is only one sector of the transportation infrastructure. Where the railway system has been considered, only economic indices were captured and investigated due to the nature and purpose of economic-based research. In terms of risk and vulnerability, a lot of the scenarios have either received no attention or were broadly mentioned as critical and significant (e.g. the effect of failure of water systems on railways) mostly at a national or regional scale, and mainly based on top-down approaches without considering details. A clear gap is observed for sector-specific metrics for railways at an engineering environment which can correlate railway operation to external infrastructures for many poorly known scenarios such as those qualitatively mentioned by RSSB (2016).

Considering the significance of resilience while confronting the growing challenges, such as new technology and climate change, a scientific approach needs to be adopted for the investigation of interdependencies of railways. Without a proper analysis, higher order effects and dependencies are difficult to understand. Therefore, this work addresses several gaps which have been found in the local/engineering level of dependency knowledge between railway systems and some other infrastructure systems.

Table 8 summarises the overall characteristics of the existing literature dealing with the topic of infrastructure dependency as discussed in this section and Table 9 presents the elements of these studies as well as their gaps and limitations.

Table 8 Characteristics of the existing literature of infrastructure systems interdependencies

Characteristic of the study	Value
General viewpoint and the focus of the research (motivation)	Conceptual and theoretical, economic prosperity and national security, risk management and facilitating resilience, big data management
Context	Security of critical infrastructure systems, system analysis and management, public work management, reliability engineering and system safety, policy and decision making, big data management, vulnerability and risk analysis and management
Dimension and factor	Spatial extent, time horizon, environment, state of operation of infrastructures, general types of dependencies, level of interaction, coupling and response behaviour, types of failure, the complexity of adaptive systems, the restart time after failure of interdependent infrastructures, the order of the dependencies, social and psychological elements, operational procedures, business policies, restoration and recovery procedures, government regulatory and stakeholder concerns

Table 9 Distinctive elements of existing literature of infrastructure systems interdependencies

Perspective/ viewpoint	**Common indices/metrics**	**Distinctive output**	**Limitations**	**Contribution to railway-related literature**	**Examples from the literature**
Conceptual or theoretical	Conceptual indices such as dimensions of interdependencies and the degree of dependency (e.g. tight vs loose)	Conceptual and qualitative results explaining how infrastructures are linked to each other as well as providing real-world examples for each	• Have neither yet captured all dimensions/factors nor compiled a comprehensive list • There is limited evidence/data available to support all sorts of theoretical dependencies mentioned	• Qualitatively describes how railway systems could be interconnected with other systems at multiple scales, dimensions and levels • Indicates the role of the railway and its potential vulnerabilities in relation with other sectors • Delineates the framework and resolution for further research studies	Rinaldi et al. (2001), Little (2002), Rinaldi (2004) McDaniels et al. (2007), CTS (2009), Ouyang, 2014, Hall et al. (2016) and RSSB (2016)
Economic	Shapes metrics or economic indices such as ratios indicating how much of the output of a given infrastructure is	Develops frameworks (or the result generated out of them) to study the equilibrium of an economy for a	• Limited to supply chain interconnection at one specific geographical scale at a time • Limited to economic indices and mainly	• At a macroscopic level explains to what extent the railway systems of a country depend on the output of other infrastructure systems (e.g. electrical power)	Barton et al., (2000), Haimes and Jiang (2001), Gursesli and Desrochers, (2003), Brown et al. (2004),

	demanded by other infrastructures	specific geographical scale	physical dependencies and unable to capture technical/engineering indices at a component level • Mainly focused on demand and/or supply driven scenarios	• Facilitates decision making for investment at a national scale	Haimes et al. (2005), Apostolakis and Lemon (2005), Lian and Haimes, (2006), Santos, (2006), Min et al. (2007), Svendsen and Wolthusen (2007), Hallegatte, (2008) and Chen et al. (2009), Oliva et al. (2010), Zio and Sansavini (2011) and Trucco et al. (2012) and Rosenberg and Carhart (2014)
Vulnerability /risk management	Core metrics and sector-specific metrics such as the number of affected customers/users because of	Develops tools (or the results generated out of them) which help quantification of interdependencies within the context of vulnerability	• For large scale system analysis, scenario-specific approaches miss several failure states and ignore parts of the system • Limited to a few scenarios (e.g. power	• Finds critical components of a railway system considering spatial, temporal and functional characteristics of systems in several risk scenarios including	Haimes and Jiang (2001), Chang et al. (2007), Luiijf et al. (2008), Van Eeten et al. (2011), Wang et al. (2012), Kotzanikolaou et

	interdependency-related failure/outage		shortage) and many scenarios are hidden/invisible due to various reasons (e.g. confidential, political etc) • The output largely depends on the assumptions regarding the criticality of the components	power outage and flooding • Facilitates vulnerability and risk-based prioritisation and hence a proactive approach towards managing interdependencies and risks	al. (2013), Wang et al. (2013), Kelly (2015), Pant et al. (2018) Johansson et al. (2007), Jönsson et al. (2008), Johansson (2010), Johansson and Hassel (2010), Utne et al. (2011), Johansson et al. (2013), Jaroszweski et al. (2014), Jaroszweski et al. (2015) and Binti Sa'adin et al. (2016)
Data management	Varies based on the usage; from shape metrics (e.g. economic indices) to core and sector-specific metrics (e.g. the effect of a new environmental-friendly strategy on	Develops tools and databases which facilitate a vast range of systemic analysis across infrastructure systems at different geographical scales and time horizons	• Requires significant time and effort and other resources (such as reliable/available data of all sectors) • Parts of the systems are ignored, and properties at	• Facilitates vulnerability and risk-based prioritisation and hence a proactive approach towards managing interdependencies and risks • Enables future interdependency-related	Barr et al. (2013), Hall et al. (2016) and Robson et al. (2018)

	the shift of the travel mode)		component level are not always captured • Computationally very expensive to evaluate the negative consequences for the exhaustive set of all failure states	research which depends on the availability a national-scale dataset	

To conclude, this section has attempted to classify the existing literature on infrastructure dependency in terms of the motive of the research, the perspective or the viewpoint, and context. However, the literature can also be categorised into different classes by the types of the methodology, modelling and simulation employed to address the objectives of the studies. The next section provides a summary of available methodologies.

2.2 Review of the approaches and models for investigating infrastructure dependency

As discussed in the previous section, research into infrastructure dependencies varies largely in content. Hence, many approaches, methods and models can be employed to investigate them. Several studies have attempted to review the existing methods, models and simulation tools and provided comprehensive overviews (Ouyang, 2014, Rinaldi, 2004, Satumtira and Dueñas-Osorio, 2010, Eusgeld et al., 2008 and Pederson et al., 2006). This section highlights the main approaches of studying dependencies and later reviews the common models and simulation tools.

Broadly speaking, regarding approaches towards studying infrastructure dependencies, two main categories can be observed in the literature: empirical approaches and predictive approaches (Johansson and Hassel, 2010). The first approach, known as the empirical approach, is based on studying past events to understand infrastructure dependencies and the common patterns they may create (e.g. Chang et al., 2007 and McDaniels et al., 2007). On the other hand, predictive approaches aim to simulate the behaviour of (inter)dependent infrastructure systems for a purpose such as studying the adverse effects of disturbances between systems using different perspectives to present the systems of interest (Haimes and Jiang, 2001, Brown et al., 2004 and Min et al., 2007). These two broad categories (empirical and predictive) can act complementarily. Empirical studies on their own can be beneficial to improve the understanding of infrastructure dependencies while these studies can also provide input for predictive models. Predictive approaches can facilitate the adaptation to future challenges and proactive risk management plans by quantifying the existing dependencies and predict future or fictional ones (Johansson and Hassel, 2010). Both approaches are explained in detail in the following sections. An overview of the empirical approach and predictive approach as well as their complementary roles are illustrated in Figure 19.

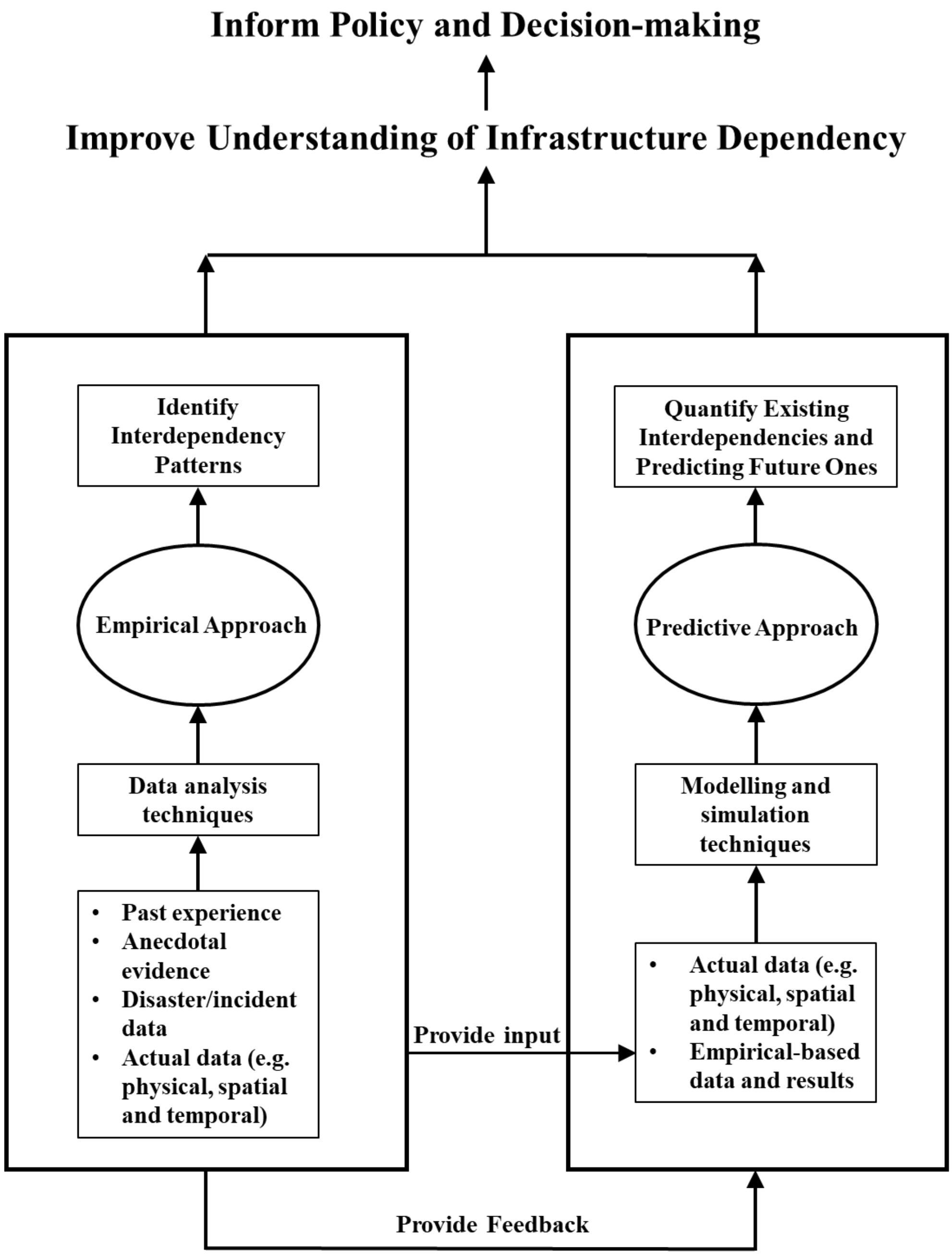


Figure 19 The overview of main categories of approaches for investigating infrastructure dependencies

2.2.1 Empirical approaches

Using an empirical approach, dependencies are analysed according to disaster data, historical incidents and expert experience. Employing this approach, the most frequent and significant failure patterns (or normal operating patterns) can be identified. An empirical approach towards infrastructure dependency is essential to identify the extent to which the society is affected by infrastructure failures caused by interdependencies. Newspapers, media reports and official ex-post assessments can help to collect incident data due to dependencies which are not evident in a normal operating condition (e.g. Luiijf et al., 2008 and Van Eeten et al., 2011) (Ouyang, 2014). For example, Wallace et al. (2001) developed a three-month database of incident reports following the World Trade Centre disaster to analyse the dependency during the restoration process. The results showed that infrastructures such as transportation and power were impacted through interdependencies for a shorter duration than banking and finance infrastructures.

Furthermore, at a component level (higher resolution) Chou and Tseng (2010) provided a database of frequent interdependency failure patterns and their occurrence probabilities. Their research presents a method to extract records of common patterns of critical infrastructure failure that are directly or indirectly caused by other infrastructure systems. The extracted data was transformed into a format required by a data mining algorithm and later the study could analyse and identify the sequential pattern of infrastructure interdependencies. A discussion on a disaster mitigation approach that could be used to mitigate interdependency-related failure events has been also included. For example, it was argued that the sequential patterns generated could be used to analyse the possibility of breaking the failure chain (cascades) disaster mitigation. Assume one identifies a frequent sequential pattern with three failure events such as (a) gas pipeline leakage (b) railway route closure and (c) coal-fired power plant shutdown, that means the gas pipeline leakage would engender an explosion which would cause the closure of the railroad/railway entrance to the coal-fired power plant and subsequently make the power plant shut down. Because of the criticality of the power plant, protection of the railroad entrance might be a good prevention strategy, e.g., creating an alternative railway route to transport the coal for fuel, or enhancing firefighting mechanisms at this railway. In other words, if a sequential pattern includes three events, and if the first event just occurred, preventing the occurrence of the middle event could be an effective strategy to protect the important component in the third event (Chou and Tseng, 2010).

Although identification of failure patterns using empirical approaches can facilitate understanding of potential interdependency failures and increase awareness regarding disasters, there are several limitations. First, the sources of data (reports, news and opinions of experts) may be biased or incomplete. As was discussed in the previous section, Luiijf et al. (2008) concluded that a lot of cascades which are identified by the operators cannot be deducted from the available empirical data. Second, there is no concrete methodology to collect failure data due to the complexity of systems and lack of standardised definitions, terminologies and metrics. Therefore, additional efforts are usually required to complement the empirical identification.

In addition to the identification of frequent failure patterns, empirical approach-based studies also quantify past dependencies observed (Zimmerman, 2001, Mendonça and Wallace, 2006, Kajitani and Sagai, 2009 and Dueñas-Osorio and Kwasinski, 2012). Indicators and metrics such as number of people affected, degree of coupling of infrastructures, resilience factor, and lag time in an incident have been proposed to empirically quantify infrastructure dependency failures. These indicators and metrics can inform future emergency decision making and act as input for predictive approach-based studies.

Furthermore, empirically-based risk analysis can be performed to study vulnerabilities according to historical failure data. Cascade diagrams, event trees, frequency of initiating events, the probabilities of involved events, the duration of subsequent events and service quality degradation have been investigated in the existing literature (Ezell et al., 2000a, Ezell et al, 2000b and Robert, 2004, Utne et al., 2011, Franchina et al., 2011 and Kjølle et al., 2012). It should be noted that because empirically-based risk analysis depends solely on failure data and experts' judgements, sufficient amounts of data are required to reduce potential errors. For instance, in an event tree analysis, the probability of any consequence depends on a single initiating event and the probability of induvial events that form a path to the unwanted consequence.

As for analysing railway-related interdependencies specifically using empirical approach, studies are very scarce. This is mainly because empirical approach-based studies rarely focus on only one infrastructure system, as they would rather investigate failures across multiple infrastructures. Examples were given above and in the previous section where transportation and railways were mentioned as part of some empirical research studies. However, as a slightly different example, Koetse and Rietveld (2009) presented a survey of the empirical literature on the effects of climate change and weather conditions (as an external factor) on transport systems, including railway sectors. 5 to 10 percent of all rail infrastructure failures (i.e. 5-10% of 8279 failures) appears to be related to weather impact in The Netherlands in 2003, which is far from negligible. Additionally, between 1993 and 2002 in the US, snow, fog and rain seem to account for 131, 81 and 411 rail accidents, respectively. This would amount to roughly 10% of all failures, which would be similar to the Dutch findings.

Note that railway infrastructure operators rarely record and document data of interdependency-related failures and incidents. A significant amount of effort is required to extract the interdependency-related information and data from such sources. For example, Zimmerman (2001) found that extraction of information from extensive reports of the National Transportation Safety Board on railroad accidents in the US showed many railway accidents have occurred or been aggravated because of a failure of communication systems informing operators of impending problems. A clear gap of knowledge is observed regarding the railway failures due to a disruption in external infrastructures and more detailed research is needed in this area. For the UK, there is a potential that information and data from RAIB (Rail Accident Investigation Branch), statistics from ORR (Office of Rail and Road), advice of safety management from RSSB (Rail Safety and Standards Board) and data from other sources such as Railway Archives can provide similar empirical data and results.

2.2.2 Predictive approaches

As previously mentioned, predictive approaches towards investigating infrastructure interdependencies aimed at simulating the behaviour of interconnected infrastructures, for example, to investigate the effect of changes in infrastructures (e.g. a disturbance or a technology change) using a variety of models. These models are namely: agent-based models, system-dynamics models, network-based models, economic-theory based models, and physics-based models, among others. This section reviews the models that support the predictive approach and provides several examples of each.

Firstly, it was previously mentioned that economic prosperity has been a major motive for the investigation of infrastructure dependencies. Therefore, economic theory-based models have been used in the last few decades to simulate and analyse the interconnectedness between critical infrastructures. Economic theory-based models are usually based on an input-output model or its extensions. The input-output model which was proposed by Leontief shows how an output from one industry/ infrastructure may become an input for other industries/infrastructures. The model shows how dependent each industry/critical infrastructure in an economy is on all other industries/infrastructures. As illustrated in Figure 20 in the input-output model, interactions between infrastructures are modelled at a high level of abstraction and hence only macroscopic dependencies could be developed. Note that the high level of abstraction introduces a simplification that ignores the structural and geographical aspects of infrastructures (Oliva et al., 2010).

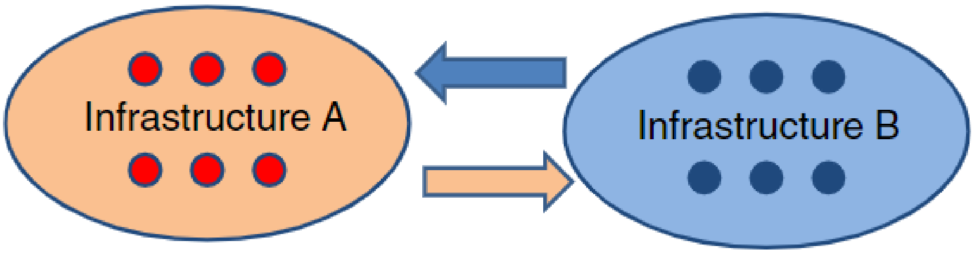


Figure 20 Schematic representation of input-output modelling of interdependent infrastructures (source: Oliva et al., 2010, figure 1.)

The equations involved in the input-output model present a static and linear model based on the technological relationships between parameters such as the number of infrastructures in an economy and the units of goods produced by each infrastructure. The output of the model can be translated into the risk of inoperability which means the inability of critical infrastructures to function normally. Inoperability input-output models can analyse the propagation of perturbations and are based on large scale databases (Ouyang, 2014). The original Leontief input-output model follows the following formula:

$$x = Ax + c \Leftrightarrow \{x_i = \sum_j x\ a_{ij}x_j + c_i\}\forall_i$$

Where the term x_i refers to the total production output from the industry i; the Leontief technical coefficient a_{ij} is the ratio of inputs of industry i to industry j in terms of the total production requirements of industry j; the notation c_i represents the industry i′s total output for final consumption by end-users (Ouyang, 2014).

Haimes and Jiang (2001) developed a general risk model based on an input-output model and investigated the dynamic risk of inoperability, given perturbations from one infrastructure, in multiple case studies. Setola et al. (2009) found the input-output inoperability model a simple but powerful mechanism for analysing the cascades between interdependent infrastructures. The study evaluated the parameters of the model based on technical and operational data (instead of typical financial data) and assessed direct higher order dependencies using input-output technique. In an Italian case study at a national scale, Setola et al. (2009) interviewed experts of different sectors to find the effect of outage of external infrastructures on their infrastructures. The study introduces two indices to better quantify the role played by each infrastructure. One is the dependency index which is defined as the sum of the Leontief coefficients (in a matrix) along a row normalized with respect to the number of infrastructures and indicates how dependent one infrastructure is on others (relatively) during an outage. The other is the "influence gain" which is defined as the column sum of the Leontief coefficients normalized with respect to the number of infrastructures and shows to what extent an infrastructure is influential during an outage. (For a detailed calculation of the indices and their examples refer to Setola et al., 2009.) Figure 21 and Figure 22 show the evolution of the dependency index and influence gain values as the outage duration increases. The data indicates that the consequences are more serious for longer outage periods. In general, it is observed that the highest influencing sector (which cause failures) is electricity while the most dependent (or vulnerable to cascades) are the air transportation and fuel and petroleum (Setola et al., 2009). As the results show, the rail sector is observed to be more depending (and hence vulnerable) than influencing.

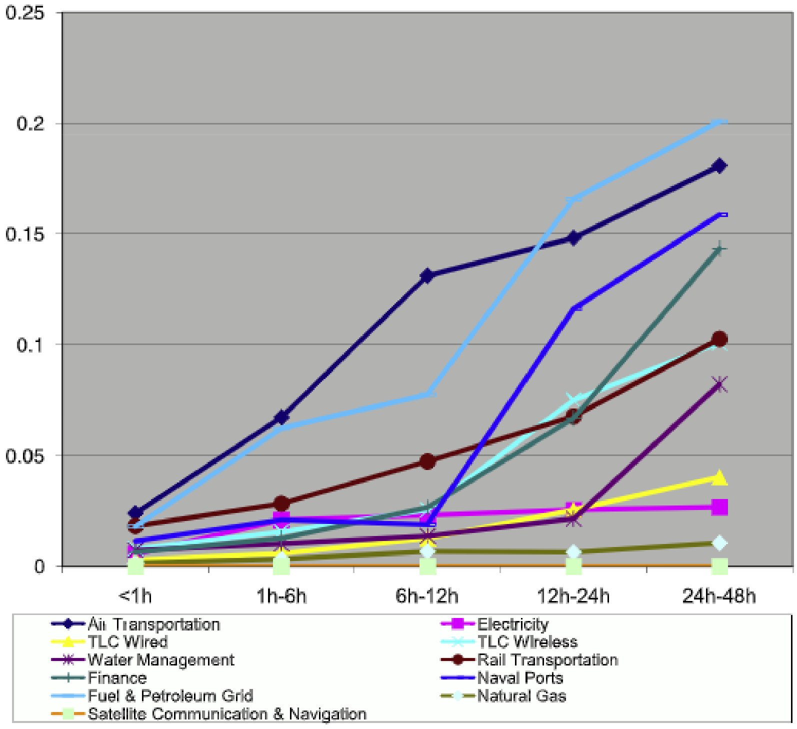


Figure 21 Dependency indices for various outage period of different infrastructure systems (source: Setola et al. 2009, figure 4.)

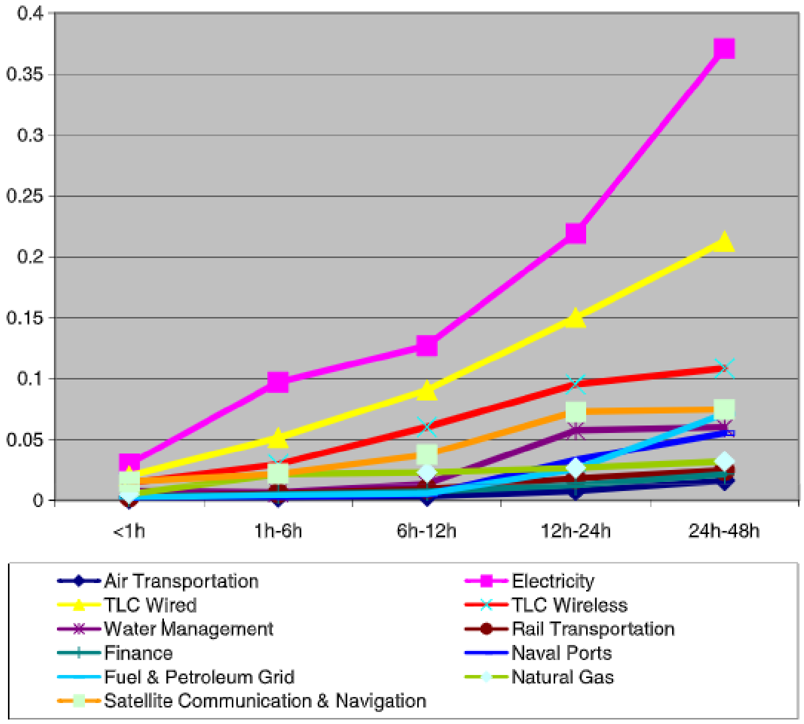


Figure 22 Influence gains for various outage periods (source: Setola et al. 2009, figure 5.)

Moreover, many models have been proposed by extending the Leontief input-output model and the concept of inoperability to predict various economic relationships and related metrics in cascade failure scenarios such as disasters and attacks (e.g. Santos and Haimes, 2004, Haimes et al., 2005 and Lian and Haimes, 2006). Ouyang (2014) recognised two weaknesses in the input-output based models. First, these models cannot capture infrastructure interdependencies at a component level as they are only useful at a macro-economic level. Second, the input-output related metrics are based on linear interdependencies among infrastructures which may not represent reality for the complex adaptive systems and hence in some cases the results could contain significant errors.

Secondly, the agent-based models adapt a bottom-up technique and simulate the interactions of autonomous agents to show the behaviour of interconnected infrastructures as complex adaptive systems. The behaviours of decision makers and the main elements in the interdependent infrastructures are modelled. The agent-based modelling technique enables users to capture all types of interdependencies among infrastructures by using discrete-event simulations and scenario-based what-if analyses. Physical components of the infrastructures, consumers, markets and decision makers can be modelled as agents. Dependencies within supply chains, telecommunications, electric power, transportation and banking can be simulated using agent-based models. Such a decomposition approach which enables dependencies to be modelled with fine granularity is illustrated in Figure 23. An agent-based modelling approach provides insight into the behaviour of each system while it is not imposing any limits on the granularity used to describe or decompose infrastructures, providing a flexible and versatile modelling framework (Oliva et al., 2010).

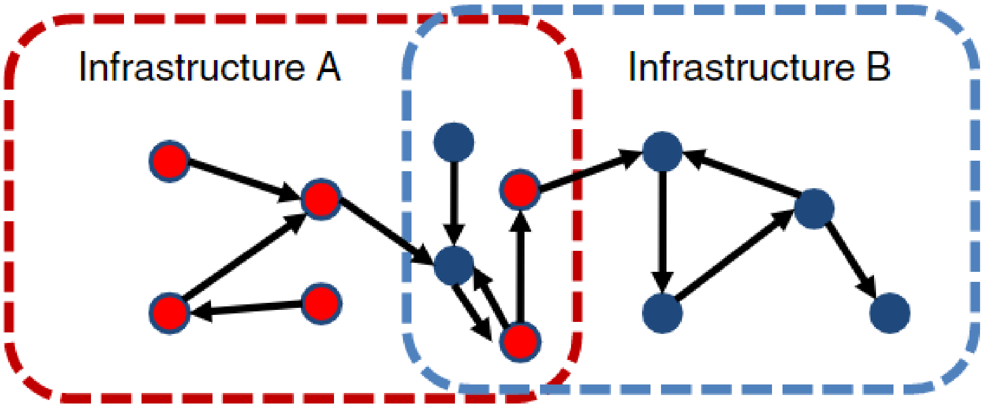


Figure 23 Schematic representation of agent-based modelling of interdependent infrastructures (source: Oliva et al., 2010, figure 2.)

As previously mentioned in Chapter 1, an agent can generally be defined as an entity with a location, some capabilities and memory. The entity location defines where it is in a physical space whereas the capability is defined as what the agent can perform, and the memory of an agent is the experience history and data (for example, overuse or aging). On the other hand, a critical infrastructure has specific behaviour while it interacts with other systems and with the surrounding environments and humans. Also a critical infrastructure system or its system components has a geographic/abstract location. At any time step a critical infrastructure is specified by an internal state that is produced by the combination of the internal state of its components. "Therefore, a critical infrastructure can be modelled as an autonomous agent and the system composed of interdependent critical infrastructures can be modelled as interacting agents which cooperate and/or compete to realise a common or an individual goal" (Casalicchio et al., 2010).

Some studies have analysed complex interdependencies among economic firms, households, power systems, telecommunications, etc., using an agent-based modelling technique (Rinaldi, 2004). At a national scale, Barton et al. (2000) simulated the effects of market decisions and disruptions/failures in power systems on other infrastructures using an agent-base model. The quantified results regarding market prices and market growth were found to be consistent with the expected economic behaviour. Furthermore, Oliva et al. (2010) dissected each infrastructure into a set of interconnected elements and considered the exchange of resources such as goods and services between sub-systems of the infrastructures. The study produced results in terms of metrics of production, consumption and transmission of resources between infrastructures related to power and other critical infrastructures. The study argued that agent-based models provide a relatively deep view of interdependencies compared to the more holistic views existing in the literature (e.g. Rinaldi et al., 2001). Agent-based models can be also integrated with other modelling techniques to provide a more comprehensive analysis (Ouyang, 2014). For example, Casalicchio et al. (2007) combined federated modelling and agent-based modelling techniques to quantify dependency-related failure scenarios of IT and power infrastructures, and found the developed tool promising. The microeconomic analyses using agent-based models help to examine the effect of disruption on firms and their ability to compete during disruption (Rinaldi, 2004). However, this type of method has several weaknesses. First, the quality of modelling largely depends on the assumptions of the researcher regarding agent behaviours. Such assumptions may be difficult to justify both theoretically and statistically. Second, it is often difficult to validate and calibrate as quantitative data of appropriate granularity may not be available.

As for the railway-related studies, the research which investigated the interdependencies using agent-based modelling for multiple sectors is rather scarce. Agent-based modelling has been used for sector-specific purposes such as intermodal transport planning (Gambardella et al., 2002 and Reis, 2014), decision making for logistic services (e.g. Roodra et al., 2010), passenger flow management (e.g. Rindsfüser and Klügl, 2007) and scheduling and flow optimisation (e.g. Blum and Eskandarian, 2002) at various scales for railways and other transportation sectors. However, studies have rarely investigated cascading (or other types of) failures or propagation of perturbation between railways and other infrastructures using agent-based modelling. This provides an opportunity for future research in this field.

The third group of models used in predictive approach-based studies are system dynamics-based models. System-dynamics based models use a top-down technique to understand and analyse non-linear behaviour of infrastructures as complex adaptive systems. As a mathematical modelling tool, system dynamics helps frame and analyse complex issues and problems such as the behaviour of complex adaptive systems. Stock, flows, feedback loops and time delays are used to represent a system usually based on the knowledge experts, available data or other sources. Stock and flow both refer to the quantities of something such as population or capital, but with different units of measurements. A stock is measured at one specific time and represents a quantity which has been accumulated in the past while a flow variable is measured as the quantity per unit of time (e.g. one week or one year) similar to the concept of rate or speed. In a systems diagram, stocks are usually represented with a box icon while flow is usually shown with a circle or pipe icon. A feedback loop (positive or negative) may exist between two parts of a system when each affects the other or when the first system influences the second one and the second one influences the first one. One simple example of this (in biological systems) could be the case of spread of a disease; the more infected people, the faster the disease will spread and vice versa. Based on stock and flow diagrams, equations are derived to characterise the quantitative relations between the variables. For instance, Santella et al. (2009) produced a system dynamics-based simulation tool of all critical infrastructures in the US (i.e. water, public health, emergency services, telecommunication, energy, transportation) and their interdependencies at an aggregate level. The model can be applied to a wide variety of disruptions across infrastructure systems and can be useful for comparison of different types of events using a consistent set of metrics. Based on the system dynamics approach, a system is broken down into simple objects or processes which interact to produce complex behaviours. The study used feedback loops, stocks, and flows to represent the system under study, based on the knowledge of a subject matter expert. Feedback loops indicate connection and direction of effects between objects and hence the dependencies. Stocks represent quantities or states of the system, the levels of which are controlled over time by flow rates between stocks. A simplified example of these components taken from a model developed by Santella et al. (2009), which shows road traffic, is illustrated in Figure 24. In the illustration, the volume of traffic present on the road (Tro: Traffic) is a stock governed by flows controlled by the entry and exit rate of vehicles, that are dependent on several other variables not illustrated. Through a series of steps (which are not shown) a feedback loop is set up between Tro: Traffic and the entry rate to the road(s) which decreases under heavy traffic conditions. The number of people successfully completing trips (Tro: Trips Completed) resulted from multiplying the exit rate by the average number of occupants per vehicle (variable not shown).

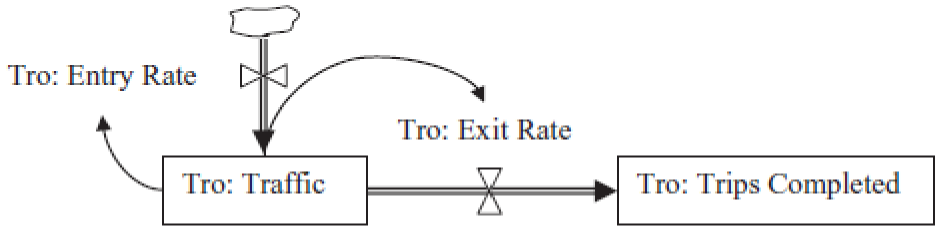


Figure 24 Simplified example of system dynamics framework for road traffic (source: Santella et al., 2009, figure 1.)

To create a quantitative system dynamics model, Santella et al. (2009) developed formulas to calculate different variables for a variety of different disruption scenarios for interconnected infrastructures. For instance, three different disruption scenarios for road systems were modelled and the results are shown in Figure 25. Here, the dependency metric is called "Trip Duration Multiplier". This metric represents the ratio of the current time needed to complete a trip to the time taken to complete a trip when travelling at free-flow speed. The free flow speed of a road is defined as the speed of a vehicle under normal operating conditions i.e. the speed limit. Trip Duration Multiplier represents quality of road service, as it measures the experience of road users. This metric can be easily translated into delay time experience by travellers or other services dependent on roadways (e.g., emergency services, delivery of supplies).

The first disruption scenario describes a 25 percent loss in road capacity which begins at the start (time = 1) of the first day (run 2A). This represents loss to capacity which might result from damage to the entire road system as in the case of a flood, earthquake or any other external event. The damage might also happen because of the failure of one asset/infrastructure, such as a bridge, which creates a bottleneck that impacts the operation of the entire road system (cascade of failures across infrastructures). As such a modelling tool considered roads in the aggregate, an estimate must be made by the user, from a transportation model or expert judgment, as to what extent damage to an individual infrastructure element would affect the entire road system. Note that this indicates the role of the experts in analysis and interpretation of the results obtained from infrastructure interdependencies-related research. Furthermore, the model assumed that roads remain at reduced capacity for the entire model run, unless additional input is included to describe the repair of roads.

The second scenario considers 25 percent of road capacity while simultaneously 25% of the population attempts to leave the city by personal vehicles over a five-hour period initiating in the early morning (shown at time = 1.3 days) on the first day (run 2B). The third scenario is the same as run 2B, but a government alert is issued requesting that only key workers report to job sites at the same time as the evacuation order (2B-EWO) and hence 90% of normal daily travel is removed. The results show that where the traffic density is low the trip duration multiplier remains at a value of one for all scenarios, so only the base run is visible. The results show that where operational capacity of the road system reduces (run 2A), the travel times increase only during normal rush hour periods by a factor of 3. In the evacuation scenario (run 2B), the extra evacuees to normal road traffic causes roads that rapidly reach capacity, resulting in traffic congestion which is expressed by a travel time multiplier exceeding the scale of the graph. In this scenario, the model predicts that traffic congestion persists for approximately 14 hours until the end of the work day and the completion of evacuation. In the same scenario, with the key-workers-only alert issued at the same time as the evacuation order (run 2B-EWO), the number of evacuating vehicles results in severely slowed traffic, while the road system does not reach traffic congestion limit and the evacuation process is accomplished within the desired five-hour period.

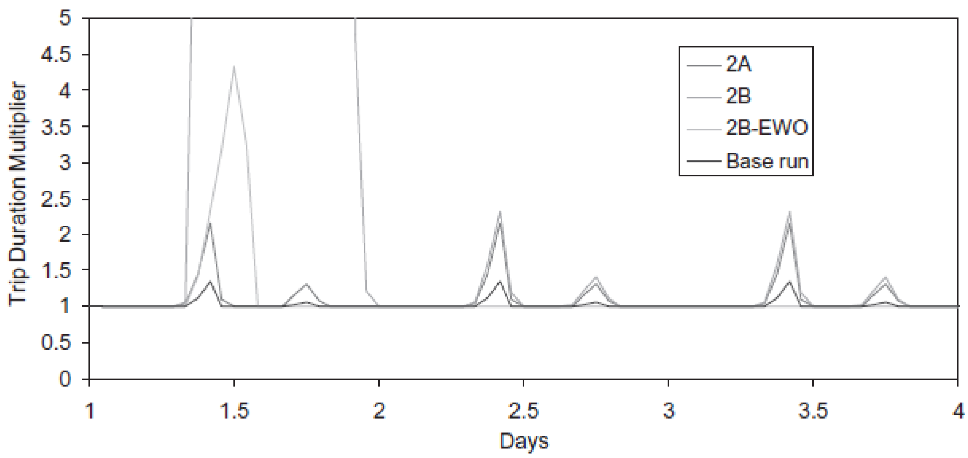


Figure 25 Modeled Trip Duration Multiplier for road damage (2A), evacuation (2B), evacuation with restricted travel (2B-EWO), and normal operation (base run) (source: Santella et al., 2009, figure 2.)

To conclude, the scenario-based interdependency study of Santella et al. (2009) could help to illustrate some general observations about modelling of infrastructure systems for decision making. It is also stated that the developed system dynamics-based modelling tool could allow for rapid creation of scenarios that support easy comparison of very different types of events and their impact across multiple infrastructures. Mitigation or response scenarios (such as the essential-workers-only alert) could be also investigated through programming of additional scenarios. This shows the capability of system dynamics modelling in analysing complex situations and systems, such as transport, at a rather detailed level and produces useful and relevant metrics for infrastructures regarding the effects they may impose on one another.

In addition to the above-mentioned transport-related example, with respect to railway-specific studies (without a particular focus on the term "infrastructure dependency"), in a Chinese case study Han and Hayashi (2008) investigated the distribution of the expected growth by mode under several policy scenarios and the external impacts of transport development on non-renewable energy use and greenhouse gas emissions. In this case, the multi-modal intercity transport system includes railways, road/highways and waterways. Three different policy-related scenarios were considered to study the effect on the modal share in the future, namely: Business as Usual Scenario (BAU), middle control scenario and high control scenario. The BAU scenario extrapolates historical data and assumes the traffic network will rise at the average rate for 2000–2005. The middle control scenario is based on the Eleventh 5-Year Plan and on policies emphasizing energy conservation and CO_2 mitigation by expanding railways and waterways and introducing a fuel tax rate of 45%. Lastly, for the high control scenario, more intensive policies are implemented concerning the environment with further investment in railways and waterways and slowing down highway expansion introducing a fuel tax rate of 50%. Figure 26 shows the predicted trend of modal share in passenger traffic to 2020. It is expected that traffic volume will reach 6600 billion p-km by the end of 2020, with an annual average growth rate of around 9%. In case of a BAU scenario, highways contribute the most to traffic growth with its share increasing 15% between 2000 and 2020. Assuming the middle and high control scenarios the share of highways is reduced because of its high energy consumption and CO_2 emissions. However, under the high control scenario, the share of railways appears to be the single largest mode by 2020 (Han and Hayashi, 2008).

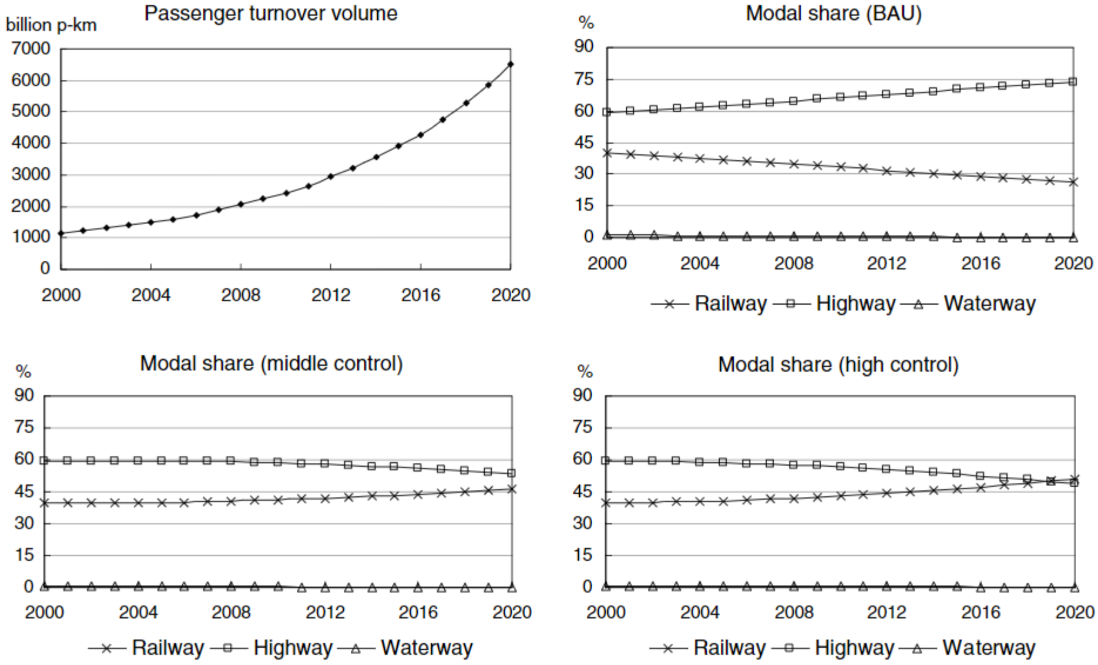


Figure 26 Inter-city passenger turnover volume and modal share in 2000–2020 (source: Han and Hayashi, 2008, figure 5.)

Note that although the both former and latter studies here (Santella et al., 2009, and Han and Hayashi, 2008) may not necessarily appear relevant to interdependency-related research for railways, the presented results indicate the wide range of metrics as well as scenarios that could be covered in the system dynamics-based modelling approach for transport infrastructure systems. Nevertheless, many more interdependency-related scenarios for railway-specific cases, such as effect of critical infrastructure failure on rail operation or the projection of demand-supply for rail freight, can be potentially investigated in the future using a similar approach.

To summarize, system dynamics-based models simulate the dynamic behaviour of the interdependent infrastructures by capturing important causes and effects under different scenarios including national scale disasters, disruptions and policy changes. The results can support future investment recommendations and protection strategies for infrastructures. However, system dynamics-based modelling has several limitations and weaknesses. First, because the knowledge of a subject matter expert is required, models can have errors. Also, the results are usually validated conceptually and based solely on reasonable responses that infrastructures may give. Second, parameters and functions in the models require calibration, which need large amounts of quantified data which are usually not easily accessible for reasons such as confidentiality. Third, system dynamics-based models are based on differential equations, which can be useful for explaining the system-level dynamics of the infrastructures but not their component-level dynamics.

The fourth group of models used in predictive approach-based studies are network-based models. Network-based models include nodes which represent components of systems (in this case, elements of different infrastructures) and links or edges which mimic the physical and functional relationships among components (e.g. Svendsen and Wolthuysen, 2007) and hence may reflect dependencies. Regarding modelling the dependencies, network-based models provide a common modelling platform and represent all infrastructures in the same fundamental way (Johansson and Hassel, 2010). Network-based (also known as graph-based) theory is an appropriate technique for modelling systems which show specific properties such as clearly defined components in the technical infrastructures. For example, Lee et al. (2007) modelled a few interdependent infrastructures, namely power, telecommunication and subway, using a network flows mathematical representation and demonstrated the use of the model in guiding the restoration of services after major disruptions. The study found that the network-based model representation helped in identifying solutions to problems associated with the disruption of interdependent infrastructures. At a more technical environment, Johansson and Hassel (2010) and Otto et al. (2016) used the fundamentals of network-based theory to study the effect of disruption in a power supply on the operation of railway systems and to analyse the vulnerability of interconnected systems. Johansson and Hassel (2010) incorporated functional and physical properties of the infrastructure systems into the conventional topological features of a network model to increase the practical value of the research. Each infrastructure is expressed both in terms of a network model and a functional model. The system's physical components are expressed as nodes (e.g. bus bar in a power system and a switch in a telecommunication system) and edges (e.g. power lines and opto-fibers). Here, the structure of a network-based model offers a common platform for all infrastructures of the interest to be modelled in the same fundamental way. To evaluate the performance of an individual system, the functional model (consisting of both physical and operational characteristics) is used together with the network model and the system's dependencies on other systems. Furthermore, a three-dimensional

Cartesian coordinate system was used to include the location of the infrastructure components, according to the geographical coordinates, to address geographical dependencies. The functional characteristic of the model resulted in the development of two types of edges, namely dependency edges, which explicitly model dependencies between different infrastructures, and the other edges within the individual systems (as previously mentioned).

To simply explain the mechanism of the network model regarding dependencies, where an infrastructure is not able to supply the demanded service, the outgoing dependency edge is removed, thus indicating the unavailability of the desired service to other infrastructures (see Figure 27). For example, where a telecommunication system relies on a power supply to operate, dependency edges exist between distribution substations in the power distribution system and nodes in the telecommunication system. When a power distribution substation loses its function, all its dependency edges to the nodes in the telecommunication system are eliminated and the consequences of the removed dependencies are assessed in the functional model of the telecommunication system. In the developed model the “strain” is a hazardous event which is supposed to affect the performance of interconnected systems. The consequences of such strains in infrastructure systems have been studied both in terms of the magnitude of interrupted services (e.g. the number and type of customers affected) and in terms of the duration of the interruption (based on the repair time) (Johansson and Hassel, 2010). An example of the results collected from this modelling tool were previously presented in section 2.1.3.

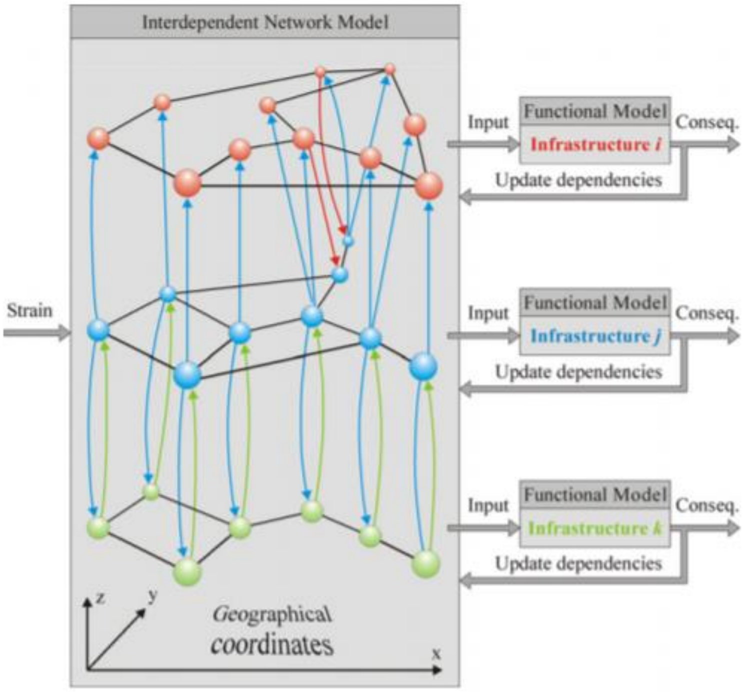


Figure 27 The overview of the interdependent network model by Johansson and Hassel (2010), figure 1.

To conclude, the above-mentioned and similar network models could be used to capture functional and geographical as well as higher order infrastructure dependencies. However, usually the functional models used are rather coarse and finer analysis requires higher computational effort and further detailed data. Furthermore, a great deal of uncertainty is involved regarding assumptions such as the repair time, which significantly affects the nature of the vulnerability related scenarios. Generally, by carrying out relatively in-depth analyses of infrastructure dependencies in a disrupted/failed operating condition (i.e. by applying strains) using the network modelling technique, the critical components of infrastructure systems could be effectively found. The technique could also provide emergency protection suggestions at a national scale, however, once more, if the detailed operation mechanisms are modelled in detail, the computational cost is very high.

There is also another group of models that can support the analysis of infrastructures known as physics-based models (Rinaldi, 2004). This group of models has not been generally recognised as a modelling tool helpful in infrastructure dependency studies. However, the outcome of these models can support the improvement of knowledge in this field, especially where the nature of dependencies simply cannot be modelled using other models. Physics-based models are based on the physical aspect of infrastructures and standard engineering tools (Rinaldi, 2004). This type of modelling has usually been used to investigate the connectedness of different sectors within an individual infrastructure, such as within an electric power grid (e.g. in a scenario of power outage) or a water supply system (e.g. in a scenario of hydraulic analyses) (e.g. López-Ibáñez, 2009 and Fernandez et al., 2013). The advantage of these models is that they can provide details down to the individual component level of infrastructures and at sector levels. However, these studies do not necessarily support the understating of dependencies among infrastructures at a national scale. Hence, while some well-defined models exist at a sector (or an individual infrastructure) level, not much effort has been observed to investigate dependencies among several various infrastructures using these models.

Furthermore, there are other models to analyse the dependencies between critical infrastructures, namely the hierarchical holographic model, the high-level architecture model, the petri-net based model, the dynamic control system theory based model, the Bayesian network based model, the population mobility model and so on (refer to Rinaldi, 2004 and Ouyang, 2014).

2.2.3 Summary and discussion

To summarize, modelling and simulation can provide considerable insight into the understanding of the complex behaviour of infrastructure dependencies and the operational characteristics of interdependent systems. Different models which consider the effect of interdependencies from different perspectives are essential for a in-depth understanding of this topic. However, the modelling and analysis of complex systems and the modelling and analysis of interdependencies between different infrastructure systems face several challenges. The weaknesses of different approaches and models explained above call for the integration of modelling techniques in a uniform analysis framework for overall decision support. Also, due to the overwhelming complexity of critical infrastructures, the effectiveness of approaches and models are limited. Therefore, it is reasonable to conclude that similarly to the way the approaches (empirical and predictive) complement each other, models can also act complementarily if they are used in combination and for studying similar infrastructure dependency scenarios (e.g. investigating the dependency between power supply and railway operation using network-based models and system dynamics-based models). Because of the complex and interconnected nature of critical infrastructures, many models have been proposed as useful tools to aid decision making by government and infrastructure managers/operators regarding these systems and their interdependencies. Table 10 summarises the approaches and models used for investigating infrastructure systems interdependencies. Table 11 compares approaches, modelling and simulation techniques based on several criteria. Note that this chapter has attempted to review the existing literature of infrastructure interdependencies and to give railway-related examples where they were relevant and available. However, one must note that since the nature of critical infrastructure systems (including technical ones) as Complex Adaptive Systems (CAS) are quite similar, all metrices and indices that have been studied for one or several infrastructures (e.g. number of affected customers) could be potentially investigated for railway systems.

Table 10 Summary of the approaches and models used for investigating infrastructure systems interdependencies

Characteristic of the study	**Value**
General approach	Predictive and empirical approaches
Model	Economic-theory based (input-output based and computable general equilibrium based), agent based, system dynamics, network based, physics based, hierarchical holographic, high level architecture, petri-net based, dynamic control system theory based, Bayesian network based model, population mobility model

Table 11 Comparison of approaches and models based on several criteria

Approach	**Modelling and Simulation technique**	**Common metrics and indices**	**Scale and level**	**Contribution to railway research**	**Examples from the literature**
Empirical	Data analysis techniques	Risk-informed metrics such as; Number of affected/dependent sectors/users/assets, Fraction of failed asset/system, Degree of coupling of infrastructures, Resilience factor and lag time	Usually international and national Macro level	Rather scarce detailed sector-specific metrics and only focusing on national infrastructure systems and the extent to which failures in railways occur because of external factors	Ezell et al., 2000a, Ezell et al, 2000b, Zimmerman (2001), Robert (2004), Mendonça and Wallace (2006), Luiijf et al. (2008), Koetse and Rietveld (2009), Kajitani and Sagai (2009), Chou and Tseng (2010), Franchina et al. (2011), Utne et al. (2011), Dueñas-Osorio and

					Kwasinski (2012) Kjølle et al. (2012)
Predictive	Input output-based modelling	Economic indices such as monetary flows of goods/services between sectors	Usually international and national Macro level	Only Shape metrics focusing on economic indices such as the cost of railways' operation at a national scale	Haimes and Jiang, (2001), Santos and Haimes (2004), and Haimes et al. (2005), Lian and Haimes (2006), Setola et al. (2009)
Predictive	Agent-based modelling	Macro and micro indices which indicate performance of systems under different scenarios such as estimated delay and downgrade resolution time	Varying from national to local Macro and Micro	Mainly sector-specific ignoring external dependencies at a national/regional scale while could be potentially very useful for resilient railway scheduling, multimodal journey planning and decision support tools	Blum and Eskandarian (2002), Gambardella et al. (2002), Rindsfüser and Klügl (2007), Casalicchio et al. (2010), Oliva et al. (2010) and Reis (2014)
Predictive	System dynamics-	Consequence and decision-related metrics (for various scenarios)	Varying from national to local	Rather scarce detailed sector-specific metrics and only focusing on national	Han and Hayashi (2008) and Santella et al. (2009)

	based modelling	such as profit and likelihood of an alternative strategy, improvement of health and safety, and restoration capability	Macro and Micro	infrastructure systems and the extent to which external factors might affect railways as a whole	
Predictive	Network-based modelling	Performance-related metrics such as the number of normal or failed components, the inverse characteristic path length, the connectivity loss, the redundancy ratio, lost service hours and fraction of users/customers affected	Varying from national to local Macro and Micro	Rather limited dependency scenarios mostly focusing on dependency of railway on electricity and ICT infrastructures	Lee et al. (2007), Svendsen and Wolthuysen (2007), Johansson and Hassel (2010) and Otto et al. (2016) (Ouyang, 2014)

Note that, in a rough comparison, some elements of the agent-based models, the system dynamics-based models and network-based models could be compared in the context of complex systems modelling or interdependency modelling. For example, the concept of stock in a system-dynamics based model acts relatively similarly to the node in a network-based model. However, a stock is usually measurable and changes according to the flow, while a node is either present or absent (a quality) based on the connected edges to it. The edges do not necessarily imply a quantity while the flows (i.e. movement of a material per unit time) must be the same type of material as the stocks they are connected to. According to Ouyang, 2014, network-based modelling and agent-based modelling need relatively more types of data compared to economic-based modelling. For example, agent-based models usually require data such as policy decision variables and human behaviour variables, while network-based models require detailed information of assets, which are usually difficult to obtain due to privacy issues. In terms of the computational effort/cost, empirical approach, economic-based models and some network-based models have a relatively lower cost, since they mainly investigate interdependencies by analytical calculation. For a comprehensive comparison of all models and approaches, refer to Ouyang, 2014.

Furthermore, note that the appropriateness of using approaches and models for railway systems or any other infrastructure systems totally depends on the purpose of the research, the perspective/viewpoint of the analysis, the dimensions of the interest and finally the properties of a system which are mainly similar in complex adaptive systems (e.g. technical infrastructures). For instance, where the purpose of a research has been defined as "finding the critical assets and components of a railway system across a country in terms of their vulnerability to electrical power outage", a predictive approach at a national scale using an agent-based or network-based modelling technique, which can capture physical and functional properties of interdependent systems at a component level (by providing a similar platform to simulate all elements), would be appropriate. In addition to the aim of the research, the literature review showed that the availability of the tools/resources as well as the desired metrics also influenced the choice of approaches and simulation models. However, it is argued that the nature of each dependency would be potentially the best motivation for further investigation rather than the availability of the data or tools. Here, it is important to remember that the main aim of this work has been defined as investigating the interdependencies between several technical infrastructures and railway systems at a local and engineering environment where gaps were observed. Additionally, note that within the vast academic literature of infrastructure dependency, very rarely were terms such as domain expert, subject-matter expert, stakeholder engagement and infrastructure decision makers detected. However, the role of such participators in the obtained knowledge was underrated. Since participator-based research significantly contributed to this thesis, the next chapter concisely reviews this topic. Chapter 3 explains the design and the overall approach of this thesis and the reasons why such an approach is required for studying infrastructure dependencies at a technical and engineering environment.

Chapter 3 The research design

This section explains the overall approach of this research for studying infrastructure dependencies related to railways at a sector, component, technical (engineering) and local level in a short to medium time range. Note that the approach of this thesis may be different from model-oriented interdependency investigations where the availability of models (modelling techniques) may cause subjectivity and directs and/or limits the scope and outcome of research. Also, the elements of the overall approach cannot be regarded as novel, but the application of grouped elements on railway-related dependencies is clearly new.

Overall, a bottom-up approach (instead of a top-down approach) has been adopted for the analysis in this thesis in order to properly investigate dependencies at a component level. Whereas a top-down approach would be suitable for analysis at socio-economical and strategic levels, a bottom-up approach would be more useful for analysis at operational and engineering/local-specific levels.

This study has been carried out based on a combination of several methods namely:

1. Reviewing the current academic knowledge and finding the gaps
2. Stakeholder engagement and participatory-based approach/modelling
3. Scenario analysis and case study (qualitative dependency analysis)
4. Modelling and simulation (quantitative dependency analysis)

These methods are explained in the following sections where employing them for this research is completely described.

3.1 Reviewing the current academic knowledge and finding the gaps

Note that Chapter 2 reviewed the current academic knowledge regarding dependencies among infrastructures and sectors and specifically the context of these studies and the common approaches and models employed by them. This helped to identify gaps of knowledge and discover useful tools to investigate dependencies. The facts as well as gaps have been identified and discussed and hence the literature review led to the objectives of this thesis. The literature review in the relevant subject also formed the basis for investigating additional studies which comprised some elements of this work (e.g. stakeholder engagement and scenario development), although studies have not necessarily focused on infrastructure dependency as the main concern of the investigation. Some of this research is reviewed in the following section where the participatory-based element of this thesis is described.

3.2 Stakeholder engagement and participatory-based approach/modelling

This section first critically reviews the existing knowledge of participatory-based research/investigation and then elaborates on how the work of this research using a participatory-based approach contributes to the knowledge of infrastructure dependency.

3.2.1 Reviewing existing knowledge of participatory-based investigation

In Chapter 2 where a thorough literature review was presented, terms such as "subject-matter expert, domain expert and stakeholder engagement" were scarcely mentioned. However, the review of the literature clearly showed that the key role and capacity of experts in adding to the knowledge of infrastructure interdependencies have been undervalued and underemphasized. In this section, a concise summary of the participatory approach to scientific research is presented to show the potential capability of this method for investigating infrastructure interdependencies. Later, it is concluded that a participatory-based approach (or stakeholder involvement) could henceforward be useful for the investigation of infrastructure dependencies.

Participatory modelling, participatory planning or, as a more general term, a participatory approach towards research can be described as employing the knowledge of non-scientists (or non-academics) for scientific purposes. The participatory approach can be explained as the methodology of incorporating stakeholders, including decision-makers at different scales, into the modelling process (Bale, 2018). It is argued that the stakeholders who are engaged in the research process (who may potentially be the end users) have the necessary domain knowledge and would be benefited from the process and/or the product (e.g. results, tools, research). The participants can help to structure the problem, describe the system and help the scientist/researcher to understand the processes involved, to create a model and to propose amendments to the model. It is agreed that better judgemental-based decisions are made with less disagreement and more success when they engage stakeholders, who are those that will be bearing the consequences of these decisions. “This leads to a more bottom-up approach, where the stakeholders play a role in knowledge generation and sharing, and the decision-making process” (Voinov, 2017). This approach is very common primarily in environmental engineering to investigate a variety of subjects, including planning and management of general environment and natural resources, water resources and water/river basins, flood risk and air pollution, etc. (see e.g. Hare et al., 2003, Yearly et al., 2003, Landstrom et al., 2011, Krueger et al., 2012, Basco-Carrera, and Mendoza, 2017). Details of participatory modelling for these studies remain outside the scope of this thesis, however, the involvement of stakeholders for such purposes was originally motivated by the increasing awareness that “the more humans impact the environment and the more they attempt to manage it, the more complex (and less predictable) the overall socio-ecological system becomes”. Hence, the idea of a participatory approach is to bring together the best available knowledge to model a complex system (Voinov, 2017).

As Figure 28 indicated, in some cases stakeholders can be used only to solicit information and to find the right parameters/input for the research models. while ideally, they could get involved in the model-building process. In some cases, the stakeholders participate in the decision-making process, a kind of “deep participation,” which usually leads to the most positive and lasting results. Note that because of the high variety of the research and the existing scenarios under investigation, it is difficult to create a generalized participatory approach strategy. However, some of the basic steps and elements are shown in Figure 29. It should be noted that there is no order in how the process proceeds. It is possible to repeat the same or previous process(es) many times or skip several processes if the objectives of the study are already addressed and management decisions are agreed upon. Note that while usually the order is undetermined, the major components of the process seem to be quite generic.

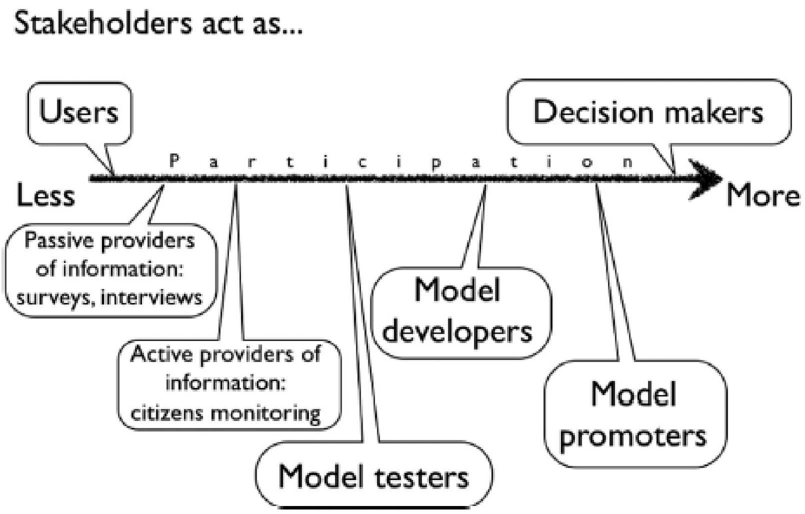


Figure 28 The different levels of stakeholder participation for a participatory approach (source: Voinov, 2017, figure 1.)

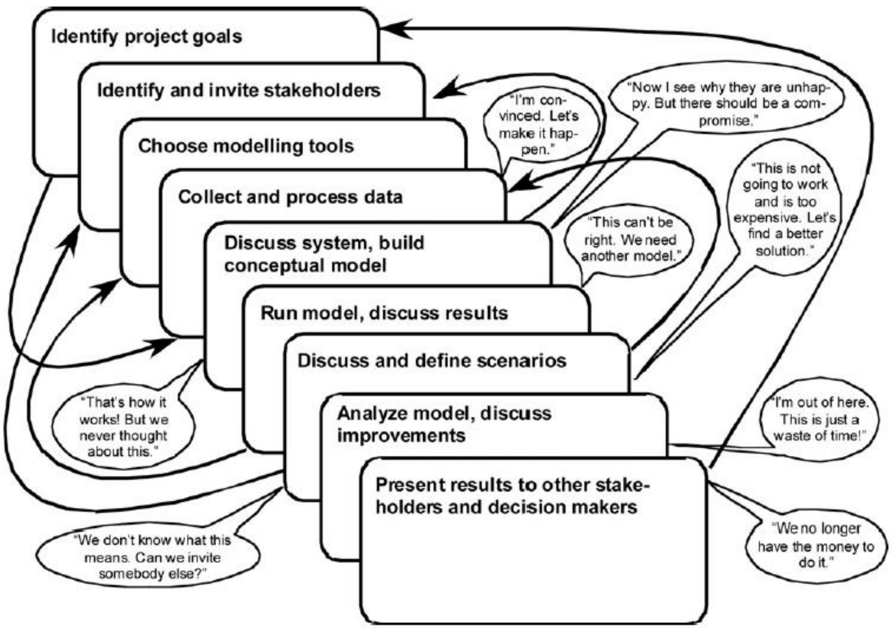


Figure 29 Different stages of a participatory modelling process including the arbitrary loops back and forth. Note that the processes can be rearranged at any point and there is no specific order in how the process proceeds (source: Voinov and Bousquet, 2010, figure 1.).

There are different types of common methods used to conduct the participatory-based investigations/study (Table 12). Based on their distinct characteristics, these methods can be grouped as the following clusters (Voinov, 2017):

1. Conceptual stage: To access the mental database of stakeholders, any participatory-based process begins with what the stakeholders think and know. At this conceptual level, the methods could be used to facilitate structuring human interaction and assisting the process of deliberations and information exchange. In addition, there are methods for soliciting data and information from stakeholders.

2. Quantitative stage: To further advance the investigation process by incorporating quantitative data and functional responses in order to understand the behaviour of systems that stakeholders manage beyond what is already known about it.

3. Reporting and testing stage. A set of methods/tools will be required to present the results in a meaningful way back to the larger group of stakeholders and decision makers (Voinov, 2017).

For a comprehensive overview of the tools and methods in participatory modelling, refer to Voinov et al. (2018), Voinov et al. (2016) and Voinov and Bousquet (2010).

Table 12 Common tools and methods for conducting participatory-based study (source: Voinov, 2017)

Main components	**Tools and Methods**
Scoping and envisioning	Meetings, workshops, brainstorming, and group facilitation, SWOT (strength, weakness, opportunities, threats) analysis, participatory scenario development, imagineering, visioning and pathways, visualisation and graphics, rich pictures, gaming, mind mapping
Data	Surveys, interviews, questionnaires, mobile applications, wikis, role-playing games, tools for eliciting expert knowledge
Model development	Conceptual and cognitive modelling (fuzzy cognitive mapping, signed di-graphs, etc.), system dynamics, agent-based modelling, Bayesian network models, cellular automata,

	scenario building, human computation, integrated modelling, optimisation, fuzzy modelling
Testing and reporting	Interactive mapping, visualisation, animations, visual analytics, web applications, games, role playing, sensitivity analysis, uncertainty analysis

On the other hand, one must note that it is crucial to identify and select the right experts for the process of participatory-based approach. The available literature included the definition of "experts" who are invited for the process of participatory modelling. According to Krueger et al. (2012), an expert can be "anyone with relevant and extensive or in-depth experience in relation to a topic of interest" and could be classified largely as a scientific (researcher) expert and a professional expert (i.e. both can be assumed as subject matter experts). Furthermore, according to Krueger et al. (2012)," experts" are distinguished from "non-experts" by "the relevance and extent or depth of their experience in relation to a topic of interest". The definition of "qualified experts" for the activities related to participatory modelling varies largely. Some restrictive definitions identified "reliable experts" as those who only have acquired specialised knowledge through training and long-term experience (practice) (Krueger et al., 2012). However, it is argued that the way experts or stakeholders who participate in a scientific research could be identified depends on the nature of the topic under investigation. For instance, in the field of environmental engineering and land management practices, local farmers and landowners could be identified as a valuable source of relevant knowledge. Note that, within the body of general academic knowledge (including infrastructure dependency research) the terms "experts" and "stakeholders" as well as the terms "opinion", "judgement" and "knowledge" are used interchangeably. Krueger et al. (2012) emphasizes that the term "opinion" is used during the initial stages of participatory modelling to indicate the preliminary state of knowledge. Opinions might not be shared by expert peers and stakeholders and would then not reflect consensus or the intersubjective knowledge of a community, although, such a distinction is not necessarily observed in the current sources. Moreover, although opinions of experts can formally or informally be incorporated into academic research, it is recommended that any opinion be translated into formal knowledge by peer review, aggregation and seeking consensus (Krueger et al., 2012). The details of knowledge formalisation vary across different disciplines and largely depends on the individual requirements of the research problem. Some of the following literature on infrastructure dependency in this section includes how opinions of the experts could be formally used for dependency problems.

Regarding the specific available literature for participatory modelling/stakeholder engagement, in relation to the studies on infrastructure dependency; Setola et al. (2009) obtained the prime research data which was used for computing/modelling from sector-specific experts. Each expert was asked to estimate the impact of outages of resources provided by other infrastructures on their infrastructure, along with the degree of their confidence in their estimates. The study assigned a reliability scale based on the experience and knowledge of the experts (as shown in Table 13) and later this information was aggregated and processed to conduct the interdependency analysis. In order to collect such data, the authors developed and used sector-specific questionnaires for domain experts to quantify the impact on the operational capability of their infrastructures (Setola et al., 2009). Note that because converting the subjective data provided by experts to cardinal quantities is always problematic, the authors codified the data in terms of fuzzy numbers as a means of formalisation to manage the data uncertainty and ambiguity, and hence to facilitate converting linguistic expressions to numerical quantities.

Table 13 Expert reliability scale assigned by Setola et al. (2009)

Class	Description	Value
A	Expert with considerable operational experience and good knowledge of the infrastructure	1.000
B	Expert with operational experience and some knowledge of the infrastructure	0.900
C	Expert with considerable operational experience but with a specific/bounded point of view	0.800
D	Expert with operational experience but with a specific/bounded point of view0	0.700
E	Expert with considerable theoretical knowledge of the infrastructure	0.600
F	Expert with considerable theoretical knowledge of some elements of the infrastructure	0.500

Moreover, Santella et al. (2009), who presented a specific system dynamics-based model, highlighted the significance and benefits of data/information provided by (many) subject matter experts. The study argued that through combination of the knowledge of subject matter experts with data from numerous sources, models can offer a greater range of quantitative information and knowledge of system connectivity and behaviour than it would be practical for one individual to acquire. However, the study emphasized that this particularly matters when evaluating the interdependence of critical infrastructure where many infrastructure systems interact, sometimes in nonlinear manners. In addition, the study also argued that indirect effects may not be well known to an individual expert in a single area of infrastructure, and without considerable study these interdependencies may be difficult to measure. For instance, the degree by which loss of telecommunications affect the functionality of emergency services or business is important in planning emergency response, or estimating economic impacts of a telecom disruption. This could probably not be easily quantified by one manager in any of these three separate fields (Santella et al., 2009). On the other hand, the study explained that, to understand scenarios across multiple infrastructures, a large amount of data from each infrastructure and expertise from many disciplines are needed. In such situations, one approach is the convening of a panel of experts to develop a comprehensive assessment. Table-top or discussion-based exercises are used to address a similar need for expertise from multiple critical infrastructure components, as well as to serve to improve communication and coordination. However, one challenge is that such group exercises are difficult and expensive to carry out, and so cannot be applied to every single question regarding infrastructures interdependencies. The study suggested that models of interactions between critical infrastructures which have been validated, ideally against real-world data and through review of subject matter experts, can complement and, in some cases, replace panels of experts, as well as inform table-top exercise scenarios. However, when examining a type of scenario which is not well-established, expert judgment is still necessary to understand limitations imposed by the model's methodology or assumptions and to direct model development and refinement as needed. Also, when the number of potential interactions between sectors is too large to evaluate, expert judgment could be used to identify and represent only the most significant interactions between infrastructures/sectors (Santella et al., 2009).

Furthermore, Oliva et al. (2010) mentioned that, for economic studies, the input-output approaches could be effectively evaluated where the availability of economic data allows the validation of the model. However, in the case of agent-based modelling approaches, where usually very little quantitative data of the appropriate granularity is available; the only choice is to obtain subjective data from asset owners, operators and domain experts. This indeed underlines the importance of engaging with system owners, operators and asset owners.

After reviewing the current academic knowledge of various fields, it is clear that some authors emphasized the importance of understanding the concerns of stakeholders and experts regarding infrastructure dependency (e.g. Rinaldi, 2004 and Pederson et al., 2006). From the above review, it could be argued that a participatory approach towards research can be beneficial and act complimentarily to an empirical and predictive approach when it is a matter of studies related to infrastructure dependencies. However, it can be also argued that the available literature concerning infrastructure dependency has not sufficiently emphasized the significance of this approach to the investigation of the effects of infrastructures/sectors on one another. Note that the academic literature presented above argued that the drive toward participatory modelling is mainly fuelled by the increasing realization that complex systems with which humans interact are better understood with the help of contributions from those who manage these systems to the investigation process. However, while the benefit of this approach is acknowledged in understanding natural environment systems, the contributions of stakeholders to understanding of CASs such as technical infrastructures are relatively neglected. In general, it can be argued that participatory-based modelling or stakeholder engagement can potentially act as an additional protection against subjectivity (related to the availability of the tools) in the research process. This is mainly because, when the research is thoroughly discussed and documented with various stakeholders involved, who may frequently have conflicting ideas, the output of problem scoping is more likely to reflect the real-world problem. Furthermore, engaging with stakeholders during the entire research/scientific process transforms the investigation into a learning process and improves the adaptiveness and flexibility of the obtained causes, drivers and outputs of the research (e.g. the developed framework or tool). The participatory-based approach also allows easier and quicker incorporation of changes which happen as complex systems dynamically evolve (e.g. natural environment and infrastructure systems).

However, several weaknesses or limitations could also be found within the technique of stakeholders' engagement. For example, stakeholders may be biased about the concerns of each sector and the degree of dependency (qualitatively stated as tight or loose) of the sectors. Furthermore, although a relatively high number of experts participated in the workshops or have been interviewed, in reality it is not practical to collect the opinion of all experts. Therefore, the range of experts may have affected the outcome. To overcome this challenge, it is important to identify the key stakeholders according to the needs of the research objectives. Limitations and potential problems of participatory-based modelling/methodology in general have been extensively reviewed and discussed in detail in the available literature (e.g. Burgess et al., 2007 and Sandker et al., 2010) but according to Voinov et al. (2016) some of these limitations include: non all-inclusive nature of participation, identification of the scale of a group of stakeholders, uniqueness of interests, needs and priorities of stakeholders, moving targets, dependence of participation on confidence-building, and trust and validity and credibility (Voinov et al., 2016).

Considering the existing knowledge that is critically reviewed in this section as well as in Chapter 2, the contribution of this research is explained in the next section.

3.2.2 Contribution of this research

In this study it is argued that experts would support the clarification of the research question based on their own concerns regarding dependencies among sectors. Stakeholder engagement is important not only in terms of understanding the current knowledge and practice within sectors, but also for supporting other methods employed in this study: scenario analysis and modelling and simulation throughout all stages of the research. In order to create a shared representation of the reality for dependency scenario development between different stakeholders and researchers and to collect input for the developed tool, a participatory modelling technique (e.g. interviews and workshops) would be beneficial. This study could result in several advantages by employing stakeholder engagement and participatory modelling. First, more technical and regional and less evident dependencies which are not detectable in academic literature could be highlighted. Most of the academic literature reviewed in chapter 2 and section 3.2.1 (e.g. Rinaldi et al., 2001, Rinaldi, 2004 and McDaniels et al., 2007, Chang et al., 2007 Kotzanikolaou et al., 2013, Pant et al., 2018, Haimes and Jiang, 2001, Luiijf et al., 2008 and Kelly, 2015) focused only on a limited number of obvious dependency scenarios between sectors, such as the mutual supply of physical resources between infrastructures. Second, because the goal of each individual sector is usually different from others and stakeholders have different concerns, such concerns may characterise dependencies and drive different requirements for modelling and simulation that can result in a combined co-simulation. Third, employing stakeholder engagement techniques could support identifying both gaps in quantified data and models and issues around knowledge sharing mechanisms between parties. Finally, stakeholders could facilitate access to relevant data as well as providing some data that is not publicly available and is known only by practitioners (e.g. the duration of a recovery process after a cross-sectoral disruption).

Therefore, this study provides a generic framework for studying infrastructure dependencies using a participatory-based approach that includes several elements, namely: scenario development, case study, modelling and simulation. These elements are explained in the next sections (3.3 and 3.4) while the generic framework is presented at the end of this chapter in the form of a conceptual diagram. Note that this research incorporates a participatory-based approach within the different stages of investigating little-known dependency scenarios across infrastructures that appeared in the form of two case studies. For each case study (Chapter 4 and Chapter 5) details of stakeholder engagement (specific to the case study and the scenario they were required to deal with) are provided. The next section outlines in general how these scenarios were developed and how case studies were chosen.

3.3 Scenario development and analysis and case study (qualitative dependency analysis) through relevant stakeholders

This section explains how different scenarios of infrastructure dependency were developed and analysed. Later, the selection of case studies and their significance are described.

3.3.1 Scenario development and analysis

It is important to note that according to the opinion of experts and literature (e.g. Johansson and Hassel, 2010) the dependencies among infrastructures are totally scenario related (especially in a failure/disrupted condition). There is very limited knowledge available about many dependency scenarios in the literature (e.g. for low probability but high consequence failures). Therefore, this study used scenario analysis as a technique to understand the non-evident dependencies. Desk studies and the knowledge of experts helped to clarify the scenarios of dependencies which caused concerns for sectors. The scenario development as a main element was started from the very early stages of this research and was carried out in parallel with identifying experts and stakeholders in an iterative process. This section explains how this process was carried out for this research.

Scenario development and identification of experts started with focusing on the main aim as investigating the little-known technical dependencies between railways and other infrastructures. Informal conversations with researchers and industrial practitioners in research program meetings (e.g. the TRaCCA program by RSSB), seminars and conferences provided a list of people (from research institutes and industrial organisations) with an interest in the topic. At this stage, where the scenarios were not thoroughly defined, through trial and error and an iterative process, correspondence started with key experts of well-known railway companies (i.e. Network Rail and London Underground). In each set of correspondence (mainly via email), first a short research proposal (including aim, objectives, motivation and benefits) was presented. Next, the contacts were encouraged to express their interest and needs regarding the topic. It was also crucial to encourage the experts to attend an in-person meeting where further discussions could be made, and more experts could be identified.

After repeating this initial stage (finding contacts and informally engaging with them) many times, the scope of the scenario could become clearer. For instance, railway experts believed that asset management for railways is a major challenge specially when external infrastructures/systems cause unexpected (and hence unevaluated) risks for railways. This led to the next step, i.e. identifying experts, where attention was focussed on more formally consulting railway route asset managers who oversee a large geographical area and are well familiar with high impact cross-sectoral risks. Several route asset managers and engineers were consulted through individual interviews where pre-designed questions were asked (e.g. regarding the external risks they identified), and the outcome was documented and collated. Moreover, a group consultation session for brainstorming was held at University College London in autumn 2015 to collect the opinions of experts on the topic of interest. Note that at this stage the scenario was still at a conceptual level. For example, experts agreed that a preliminary step to understand some little-known dependencies was to investigate how different sectors at a regional scale interact in a technical environment, before attempting to narrow down a specific scenario and quantify it. Also note that at the beginning of every engagement activity (follow-up meetings, interviews and brainstorming sessions) with stakeholders for the scenario development, it was crucial to brief them. Briefing could ensure that all interviewees/participants had the same level of understanding about the purpose (i.e. developing a clear dependency scenario). Such consultations resulted in identifying more specific experts who had both the interest and resources (time, knowledge, data, etc.) to support the research.

When the scope of the scenarios had been clarified and progressed from a conceptual level to a contextual level, experts within the dependent sectors (non-railways) could be identified. At this stage it was agreed that power production and urban water supply, as two crucial sectors, include interactions with railways that deserve further attention. Therefore, iteratively, the above-mentioned steps were repeated to engage with experts of these (external) sectors in order to agree on a common scope for the scenarios. For the power sector the most relevant stakeholders could be identified as those at power stations and the National Grid, while for the water sector both clear and wastewater divisions of water companies were found to be relevant.

3.3.2 Case study

At this stage of scenario development, this research started using a case-study approach to investigate dependencies that exist between railway systems and the two technical sectors/infrastructures. This was mainly because infrastructures and sectors are so complex and hence there was little possibility of identifying an industrial expert who could provide knowledge for a detailed technical scenario outside the geographical area they oversaw. Therefore, it was agreed to develop the scenarios in terms of dependency between rail and power systems as well as between rail and urban water system for cases where interested experts had already been identified through previous stages. Several benefits of adopting a case study approach for this research could be identified. First because case studies provide details at a component level for infrastructure dependency related analyses and therefore can be useful for producing high resolution quantified results. Second, because real-world (and not fictitious) cases have been studied, the results could potentially be used to explain similar cases.

Moreover, case studies could also deliver benefits for the experts who largely contributed to this research by providing them an opportunity to express their specific needs (from the research) and collaborate with each other. It was agreed that two case studies would be conducted in this research. They focus on regional and technical dependencies that exist and were previously little-known. The first case study investigated a dependency that exists between electricity generation (power output) and freight railway traffic. It focused on the freight route from/to the Port of Immingham in North Lincolnshire, UK, which is a major freight route connecting different infrastructures, including the port and the Electricity Supply Industry (ESI) (power stations in the area). This case study can be a presentation of interdependency at the national scale (due to the significance of the power plant in the case study from the viewpoint of national electricity supply) which may be exposed to local risks (disruption of freight traffic due to the failure of a rail infrastructure such as a bridge). The second case study of this thesis evaluated the dependency that exists between railways and the urban water distribution system in a scenario of track flooding caused by a water main burst. It focused on the Thameslink railway and Thames Water assets in the London area. This case study can be a presentation of geographical interdependency at a local scale and a type of cascading failure (e.g. flooding cascades through geographically interdependent infrastructures). The two case studies were chosen for various reasons. First, because the author and experts agreed that they provide a great and generic example to meet the aim of the research. Second since they were the only cases for which, due to their critical importance, all stakeholders relevant to the scenarios provided significant support (through time, knowledge and data) throughout the research. Further details regarding the importance of both case studies due to the observed gaps and serious vulnerabilities are included in Chapter 4 and Chapter 5.

Note that the process of scenario development continued and evolved for this research to extract several clear engineering scenarios at a contextual level through case-specific engagement with experts and stakeholders. Details of such case-specific engagement are elaborated in detail in Chapter 4 and Chapter 5. At this contextual level, quantification through modelling and simulation were employed for this research. These elements are briefly outlined in the next section and are elaborated extensively for each case later in the relevant chapters.

3.4 Modelling and simulation (quantitative dependency analysis)

Last but not least, modelling and simulation techniques have been used to quantify the dependencies which have been highlighted qualitatively by stakeholders and as scenarios. The modelling and simulation techniques have been chosen based on the requirements of the case study, the available input (data) and the type of output (indicator or metric) useful for the research. For the first case study different time-series analyses have been carried out, whereas in the second case study hydraulic (physics-based modelling) and numerical simulations have been used.

The outcome of the first case study (dependency between power supply and railways) is presented in the form of identifying as well as conceptualising a dependency between two sectors, whereas for the second case study (dependency between urban water systems and railways), in addition to identification and conceptualisation of the dependency, the developed model can potentially act as a generic tool to quantify any burst-induced railway flooding. In both cases, this thesis tried to understand non-evident dependencies as a first step towards developing a numerical evaluation (which would eventually help risk quantification). Note, non-evident dependencies (or alternatively little-known dependencies) in this thesis are defined as those connections between infrastructure systems which are either fully absent in academic literature or are left unassessed or unevaluated. It should be noted that this study took the step of scenario development and case study before developing any modelling and simulation, while most of the available studies at a technical environment developed ready-to-use system-level tools (system dynamics-based, agent-based and network-based) which could later be used for a number of scenarios (e.g. Johansson and Hassel, 2010 and González-Gil et al., 2014). Because these tools are not designed specifically for studying particular scenarios, simplifications of inputs may be necessary. Hence, in fact, the limitations of the tools affect the extent of the scenarios able to be investigated. However, in here, every tool or modelling technique which is employed has been designed based on the nature and details of the dependency scenarios. This approach ensures that the critical elements of the scenarios are fully captured and simulated in order to represent the reality.

To summarize, because the above engineering scenarios required a component-level evaluation, theory-oriented macroeconomic and descriptive approaches (presented by Rinaldi et al., 2001, Rinaldi, 2004 and McDaniels et al., 2007) could not be utilised for investigating the dependencies. On the other hand, the scenarios could be evaluated by simpler, yet effective, techniques rather than complicated ready-to-use models (e.g. system dynamics-based models) which may also impose limitations on the input and the output. The nature of the dependencies in the scenarios could not be captured by system dynamics-based, agent-based and network-based models, and in the second case study the physics-based modelling could provide an effective tool for further evaluations. The next section provides an overview of the design of this research including its elements and how they are related with each other.

3.5 Summary of the current research design

This chapter described the overall approach of this research to investigating infrastructure dependencies related to railways at a sector, technical (engineering) and local level in a short to medium time range. A review in the field of participatory modelling was carried out and it was argued that engaging with relevant stakeholders and experts could be key to improving the understanding of interconnectedness of complex systems. The chapter later described broadly how this research contributes to the body of knowledge by exploring non-evident dependency scenarios through case studies. Scenario development, case study selection as well as the identification and engagement with stakeholders for this research were described. Finally, it was explained that the engineering scenarios were quantitatively investigated to provide beneficial results and a generic quantified tool.

A generic framework is presented as a conceptual tool to demonstrate how different elements of this research work together for investigating dependencies. An overview of this framework in the form of a graphical representation is presented in Figure 30. Regarding the generic framework (as shown graphically in Figure 30), the elements mentioned in this chapter are presented in the shape of blocks, such as identifying experts and engaging with them. Some blocks represent individual entities while others show a group of them (e.g. information, concerns and needs). Entities could be considered either as a process to carry out, such as “case study selection”, or as a status of research, such as “research outcome”. According to the research design, the research starts with a research question at an opinion and idea level (as illustrated at the top left and the bottom of the diagram) and moves to a more conceptual phase when information, concerns and need are explored through engaging with experts. As mentioned earlier in this chapter, the participatory-based approach for research is an iterative process, which by nature moves from one entity in the diagram to the next through some interactions/functions such as “supports” including many (optional) feedback loops (as shown by dotted arrows between entities). Note that feedback loops are not limited to those shown on the diagram but could be assumed between any entity and an earlier one (in the process) where required. For the design of this research, all the entities included in the figure have been employed and some of them were repeated many times. However, the elements can be eliminated for other research projects based on the scope and the target of the project. Also, when considering the feedback loop from "seeking and incorporating feedback" to "engaging with experts" usually very few of the processes in between the two need to be repeated.

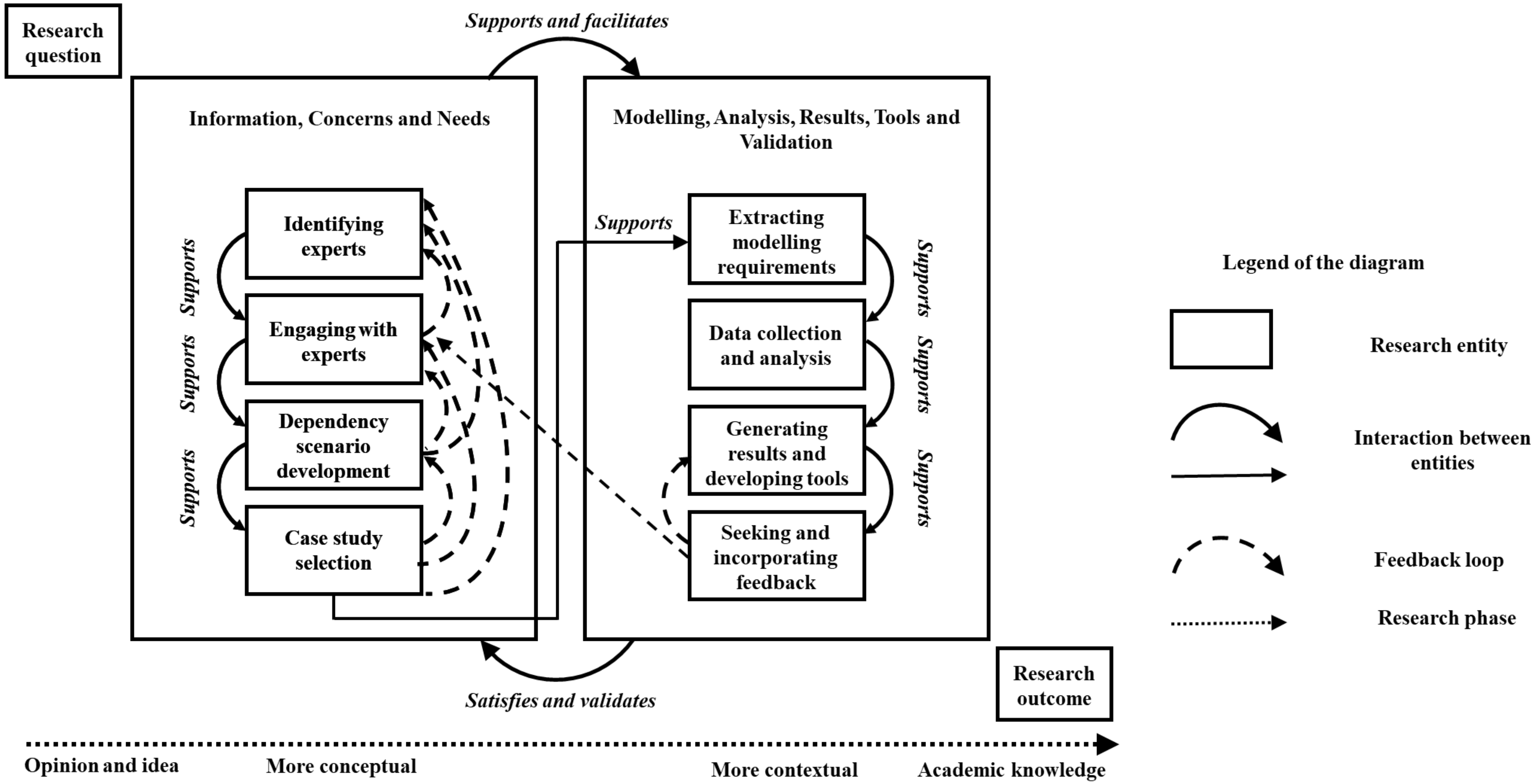


Figure 30 The generic framework of this research (by the author)

Note that opinions and knowledge of experts are incorporated into all elements, processes and techniques mentioned here. Therefore, engagement with industrial stakeholders and subject matter experts are continuously encouraged and effectively employed during all phases of this research. Regarding various techniques or methods of engagement with experts, Table 14 shows the strategy that this research suggests and used. As the table shows, this research carefully considered the group size when engaging with experts at any level. For the early stages when objectives and scope are not clarified and the research is at a very conceptual level, it is not beneficial to engage with a large group of experts. Instead, individual conversations as well as desk study can be more effective to narrow down to a clear aim and find relevant contacts for the next steps. During intermediate stages where the research moves further from opinion and ideas to a purposeful project, both individual and small group engagement and medium to large group engagement can bring certain benefits, such as agreeing on the scope of the research and details of engagement of experts. However, for workshop and feedback sessions where usually a consensus of opinions is required, medium to larger groups are preferred. It is argued that the larger number of the participants in these sessions does not necessarily add value. Large numbers of attendees in some cases can cause disruption, unnecessary distraction, moving targets and wasting time to group sessions. Hence, the researcher needs to ensure that a sufficient but not redundant number of participants who are capable of representing their sector/infrastructure regarding the topic of interest are present.

Furthermore, the structure and design of engagement sessions (meetings, interviews and workshops) are explained in the relevant chapters. The explanation includes the structure of the sessions, the questions and exercises, the outcomes and methods of collation and analyses. This research suggests that such details need to be decided upon and specified in a bespoke manner and hence no strict rule or strategy is instructed here.

Table 14 Main methods of engagement used in this research

Method of engagement	Type	Main purpose(s) and benefits
Conversation and correspondence	• Individual and small group engagement	Collecting initial research ideas, motivating to participate, identifying contacts inside and across sectors, asking sector specific and relevant questions, etc.
Meeting	• Individual and small group engagement	Collecting initial research ideas, motivating to participate, identifying contacts inside and across sectors, asking sector specific and relevant questions and observing documents and data that cannot be shared through correspondence
Interview	• Individual and small group engagement	Asking sector specific and relevant questions, problem scoping, completing pre-designed questionnaires and collecting more formal information
Brainstorming session	• Individual and small group engagement • Medium to large group engagement	Discussing research objectives, negotiating shared benefits, brainstorming about the project scope and details of engagement
Scenario development session	• Individual and small group engagement • Medium to large group engagement	Clarifying research objectives, agreeing on shared benefits, agreeing on the scope and details of engagement, case study selection and clearly developing dependency scenarios
Workshop	• Medium to large group engagement	Collecting consensus for pre-designed dependency scenarios/problems and collecting input for quantitative models (e.g. variables and parameters)
Feedback session	• Medium to large group engagement	Seeking, receiving and using feedback from participants who engaged at various levels of the research

To conclude, for the current study (this thesis), a combination of participatory-based methods (meetings, workshops, brainstorming sessions, scenario development, interviews), as well as academic approaches (such as data analysis, physics-based modelling, numerical simulation and sensitivity analysis) have been employed to complete the research. The elements mentioned (e.g. case specific interviews and workshops) and will be described further and in detail in this thesis where required. However, the core of all these methodologies/tools was intended to be the involvement of stakeholders (participatory-based approach), which is based on the idea of bringing the best available knowledge to understand a complex system (in this case a system of infrastructure systems) to add to the available academic knowledge. The next chapter presents the first case study and investigates and evaluates a dependency that exists between railways and power production sectors using real data.

Chapter 4 Case study: Railway system and power generation system

This chapter investigates a dependency that exists between electricity generation (power output) and freight railway traffic using a participatory-based approach (e.g. opinions of experts) and analysis of the data related to sectors. In order to meet this goal, the following objectives have been addressed:

- To explore the dependencies that exist between electricity power generation and freight railway service (section 4.1)
- To carry out a critical literature review of existing knowledge in this field (section 4.2)
- To devise the methodology to investigate the dependency (section 4.3)
- The selection of a case study area based on a preliminary study and engaging knowledge of industrial experts/stakeholders (section 4.4)
- To outline the sub-framework employed for analysing a dependency between railway systems and power generation systems (section 4.5)
- To qualitatively investigate the existing interdependencies and understand the dynamics between systems in the case study area (section 4.6)
- Evaluating the dependencies against the current operation by analysis of the available data for the case study area (section 4.7)

4.1 Background

This section provides a background to explore and acknowledge the dependencies that exist between electricity power generation and freight railway service.

It is usually stated that, globally, the electric power production sector requires road and rail transport (as one of the discrete events of the supply chain) to supply bulk commodities (e.g. coal and biomass) and large manufacturing components (e.g. Rinaldi et al., 2001, MDS, 2018, AAR, 2020 and RFG, 2020). In many countries, including the UK, freight railways resupply fuel and ship components for the electric power production system. It is assumed that the supply needs to be regular and reliable. In the UK, it is clear that some types of electric power production (e.g. coal-fuelled) largely depend on rail freight transport. Interviews showed that at a national scale, the railway has a 95% market share of coal supply to inland power stations (Network Rail, 2013). For biomass, it is assumed that the railway has a similar share, and indeed at Drax power station the imported biomass, which accounts for 97% of the total biomass consumed in the UK (Drax, 2015), is all transported by the railway (the same freight railway selected for this case study).

Figure 31 shows the annual coal flow (in million tonnes) in the UK for 2015 (DECC, 2015). The coal flow is shown using Sankey diagrams where the width of the arrows/bars is proportional to the flow rate (Schmidt, 2008). The figure shows that the UK mainly relies on imported coal. This suggests that the process of importing coal (through ports) is essential for electricity generation.

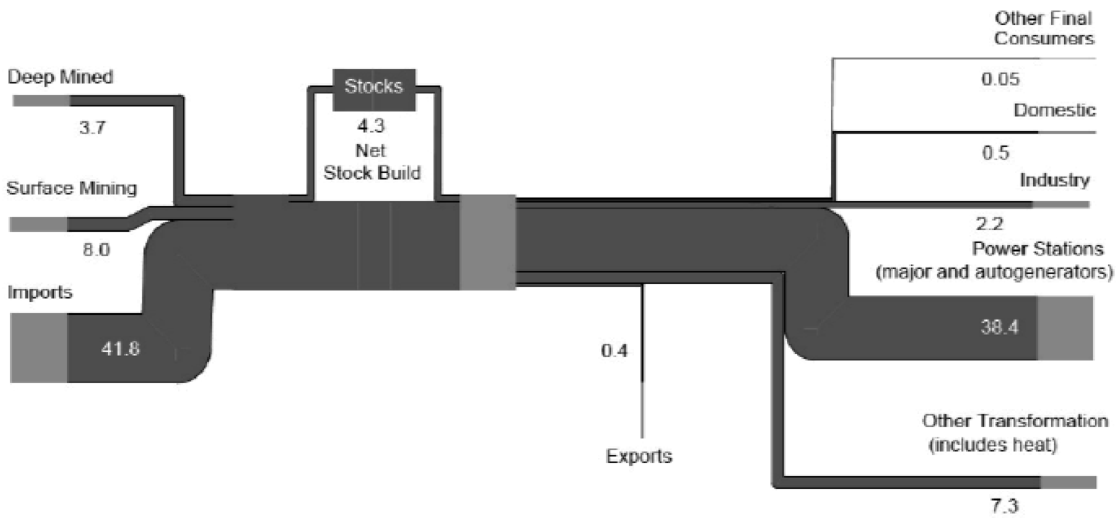


Figure 31 Coal flow in the UK in 2014 (extract from DECC, 2015, Coal flow chart)

Unit: Million tonnes of coal

On the other hand, the UK national energy trend shows that energy from renewable sources has been steadily increasing since the year 2000 as a result of national and international incentives including the EU Renewable Energy Directive. "The Directive requires the EU as a whole to achieve 20% of its energy from renewable sources by 2020 (the UK's target is set at 15%)". The UK has a varied mix of renewable technologies, including biomass, which is a key fuel source in both electricity generation and heat (DECC, 2013). Figure 32 shows that currently coal is the main source for electricity generation but will be gradually replaced by renewable resources (including biomass).

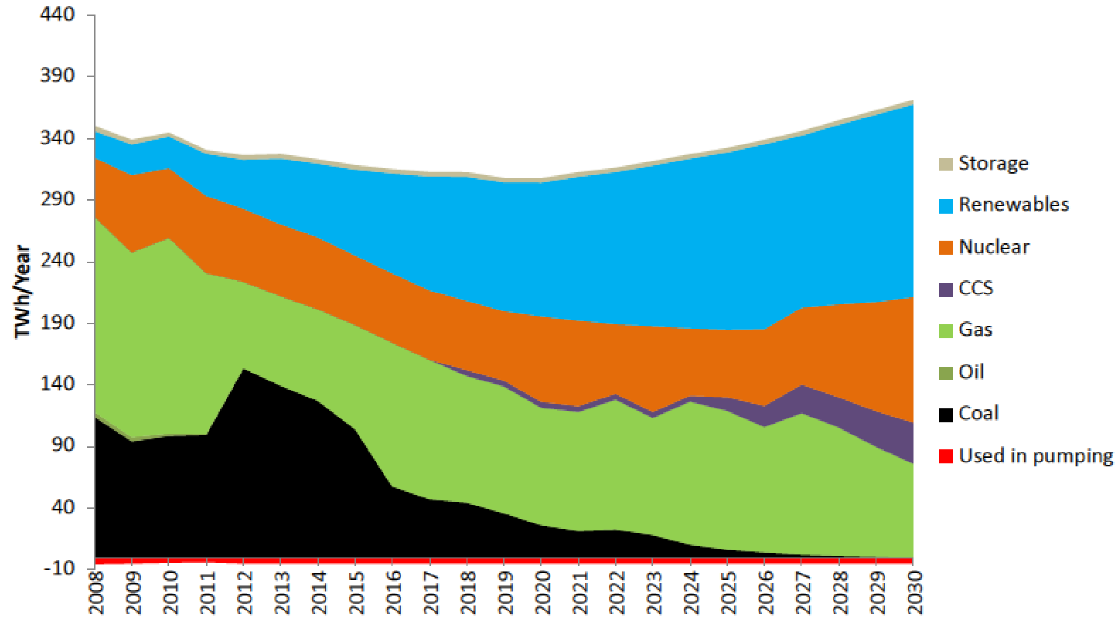


Figure 32 Electricity supplied by fuel for the major power plants, 2008 to 2030 (extract from DECC, 2013, Figure 6.2)

In 2017, coal's share of power generation fell further to 6.7%, from 9.0% in 2016 and 22% in 2015, as some coal plants have closed or converted to biomass (National Statistics, 2017). Note that around 9% of the electricity generated in the UK is from biomass, given that, although there is no individual figure for biomass generation, most of the 'bioenergy' is thought to be biomass (DECC, 2016). Regarding biomass (i.e. wood pellets, which are used for electricity generation), the UK production of this is currently low and biomass has not yet been widely used as a source of energy. In 2014, the UK produced biomass was 2.7% of the entire biomass used for electricity generation (Drax, 2015). According to DECC (2015), "there are currently only two power stations whose generation capacity is more than 1000MW that use biomass, namely, Drax and Fiddler's Ferry (at Warrington)".

While coal as the current main source for electricity generation will be gradually taken over by renewable resources (including biomass), the impact of such replacement on interdependent infrastructures is not fully known. On the other hand, interviews with experts showed that the logistics of biomass and coal supply could be complex and different from one another. This complexity may impact the dependency that exists between the two infrastructures. Therefore, this case study attempted to investigate the dependencies that exist between different freight railway traffic and power outputs at power stations using relevant information and data related to sectors.

4.2 Literature review

This section reviews the academic knowledge related to the dependencies that exist between railway systems and electricity power generation systems. Later, the gaps observed in the existing knowledge are discussed.

Infrastructures of a railway network and electricity power generation system are physically interdependent, taking into account that each supplies commodities the other needs to operate. Railways transport coal, fuel and large repair and replacement parts to the power plants. On the other hand, the electricity which has been generated by power plants powers the assets of the railway system (i.e. signals, switches, control centres and stations). Also, in case of an electrified railway system, the electricity directly powers the trains. Given that the linkages are mutual, the dependency of infrastructures including transport (e.g. a railway) on the electricity supply has been studied in the past in only one direction from the viewpoint of different interests, including failure of dependent infrastructures, energy optimisation and efficiency and system-level management and planning (e.g. Amin, 2004, Chang et al., 2007, McDaniels et al., 2007, Johansson and Hassel, 2010, Carreras at al., 2012, González-Gil et al., 2014 and Calvillo et al., 2016).

Additionally, there are studies available regarding the dependency of electric power production on transportation and more particularly on rail transport. The available literature could be categorised into two groups. The first group includes studies which macroscopically and economically study the dependency using input-output analyses and top-bottom approaches (e.g. Rinaldi et al., 2001, Haimes et al., 2005, Santos, 2006, Setola et al., 2009, Gao et al., 2012 and Francis and Bekera, 2014). These studies either qualitatively describe the relationship between the two sectors and the contribution of the dependencies to the economy, or quantitatively investigate the impact of disruptions to the operability of each sector. They provide invaluable insights into the security and resilience of critical infrastructures at an abstract level. While being qualitative, in many cases the academic literature presents a fair overview of dependencies between infrastructures. For example, the degree of dependency as a relative metric has been addressed in the literature. Degree of dependency/coupling of infrastructures which influences adaptiveness and flexibility of infrastructures is indicated by the broad and relative terms "loose" and "tight". It is stated that tighter and more complex interdependencies lead to a higher risk of infrastructure failure. For example, it is mentioned that coal-fuelled power plants loosely depend on a freight diesel-powered railway network because power plants usually can store up to three months of coal supply (Rinaldi et al., 2001). There is no information available in the literature regarding the tightness of dependency in the case of biomass-fuelled or co-firing power plants. Overall, the nature of detailed technical/engineering dependencies cannot be easily captured by these studies as they usually investigate at a system level and not at a higher resolution.

The second group of studies include those which investigate the supply chain for the power sector (e.g. coal and biomass supply). These studies do not necessarily consider the linkages between two sectors/infrastructures but merely focus on the details of electric power supply chain management. Concerns around the supply chain for the power sector vary according to the type of commodity, namely coal and biomass. Challenges of sustainable supply and logistical issues such as the handling and storage of coal have received attention (e.g. Peng et al., 2009, Pan et al., 2012 and Gedik et al., 2014). For biomass, some studies focused on the investigation of improved storage solutions as a critical link in the biomass supply chain (Allen et al., 1998, Sokhansanj et al., 2006, Rentizelas et al., 2009 and Roni et al., 2017). It is apparent that biomass degrades if stored with high moisture content without drying. This can result in material loss as well as health and safety problems (e.g. fire danger and formation of microbes). Natural biodegradation of biomass in storage leads to loss in energy production, therefore, technically, it is not possible to have a large quantity of stock (Biomass Energy Centre, 2011). One low cost solution would be to shorten the storage time and provide a frequent supply. Reviewing the literature regarding supply chains provides useful information and technical details about the bulk commodity supply chains for the power sector. However, because the broader picture of infrastructure dependency has not been the focus of these studies, there is no investigation into the impacts of such technical details. Information and knowledge such as the link between the frequency of supply and the amount of production have been missing and unaddressed.

It seems that solutions such as different handlings and storage of biomass may result in different degrees of dependency between freight railway supply and power production than of that for coal. For example, practitioners (experts) believe that, unlike for coal supply, the power production infrastructure highly depends on freight railway for biomass supply. There is no recognition of such different dependencies available in the literature and no suitable data or methodology exists to address them. However, it is stated that infrastructure dependency regarding biomass-fuelled power plants requires particular attention as government regulations support conversion to biomass in the future.

On the other hand, supply chain risk management has received attention in the academic literature. Due to the vital role of effective operations of supply chain, researchers focused on supply chain risk management by contributing in the areas of defining, operationalising and mitigating risks (Ho et al., 2015). Example of supply chains disruptions that have impacted the performance of businesses in the past includes, a drop in Toyota's production due to the tsunami in 2011, and disruption to the supply chain of computer manufacturers due to Thailand flooding in 2011 (Ho et al., 2015). The academic literature suggests that in order to secure the healthy functioning of supply chain in an economy, sectors of: information technology (Chopra and Sodhi 2004), transportation (Wu et al., 2006) and financial systems (Chopra and Sodhi 2004 and Wu et al., 2006), are of vital importance. Any disruptions in these systems can lead to serious problems in a supply chain and the risks relating to these three systems are classified as infrastructural risks. Despite such realisations, there is a major lack of research studies at the individual sector level analysing the impact of supply chain disruption (e.g. by rail) on dependent sectors. Additionally, the concern of investigation into supply chain risk management, is that it has been mostly focused on the implications and optimal solutions for customers/consumers. However, there is a gap in knowledge regarding the influences of local and engineering level infrastructure dependencies on supply chains such as Electricity Supply Industry (ESI).

To summarise, taking experts' judgement into account, it is believed that the actual links between systems in some cases appear slightly different to what the literature has indicated. Hence, the picture of dependencies may become more complete if further research improves the understanding of real-world scenarios. Using the existing knowledge in the literature together with information from experts as a valuable basis, this case study investigates the dependency that exists between two critical infrastructures at a technical and engineering environment. Section 4.3 describes the method employed to carry out the dependency analysis.

4.3 Method

As previously mentioned in chapter 3, this study used a combination of literature review, stakeholder engagement, and scenario analysis as well as case study and quantitative analysis in order to investigate railways related dependencies. As for the current scenario; the dependency between electricity generation (power output) and freight railway traffic, the overall method employed is as follows.

First, the literature review carried out in section 4.2 showed that while the power dependency on railways in a normal operating condition has been qualitatively explained in the literature, there is a lack of quantified evidence at least within the scope of dependency-related studies. On the other hand, government reports (e.g. DECC, 2013 and DECC, 2016) showed that bioenergy, including biomass, will be a key source of future energy in the UK. Although almost all biomass in the UK is transported by freight railways, no current study has evaluated the dependency of biomass-fuelled power production on freight railway traffic. It is therefore reasonable to conclude that the dependency between biomass-fuelled power plants and railways requires further attention.

Next, interviews with experts and workshops at which stakeholders participated revealed more gaps in the knowledge, such as poorly understood vulnerabilities of electricity generation due to its dependency on railway infrastructures. Furthermore, because investigation into non-evident interdependencies would require a detailed local-scale study, this study employed a case-study approach and focused on a small part of the UK railway network. The details of the case study area selected for the investigation is collected through literature reviews, engagement with stakeholders and site visits summarised in section 4.4. Dependencies in the case study area were discussed in a workshop at which local engineers (i.e. engineers who oversee the operation and maintenance of the assets in the case study area daily) and managers participated. The workshop approach was employed because local engineers and managers would know (or at least have some clues about) non-evident interdependency scenarios and a workshop would be an effective approach to collect information regarding these. The findings from interviews and workshops are summarised in section 4.6. Ultimately, although many dependencies could be explained by stakeholders qualitatively, there is a lack of data and relevant analyses/models to quantify them. Hence, in section 4.7 the dependency of electricity power generation on railway traffic is evaluated and quantified using data provided by the sectors. Such quantifications are conducted using data analysis techniques and appropriate statistical methods in order to better interpret the dependency behaviour.

4.4 Focusing on a case study area

This section investigates the case study area focusing on the port, the railways and the commodity movement to provide background information for the dependency analyses conducted later (in sections 4.6 and 4.7).

4.4.1 The port of Immingham

This research focused on the port of Immingham (Figure 33) due to its importance for the UK's economy and society. The freight railways which connect this major port to several critical sectors in the UK have created a vital supply chain and cases of critical interdependencies which provide great examples for this research. Therefore, this section focuses on introducing the area of the case study.

Figure 33 Position of port of Immingham in England (source: Google Maps)

Firstly, port of Immingham owned by ABP (Association of British Ports) is one of the UK's busiest ports, which as a vital transport hub, contributes to the economy and wellbeing of the UK. It is a global trade gateway and is of national economic and strategic importance, handling key trades such as: crude oil, petrochemicals, coal, iron ore, biomass, wind turbine components, agribulks and unitised cargo. It is also the UK's largest port by tonnage, handling up to 55 million tonnes, including nearly 20 million tonnes of oil and 10 million tonnes of coal per year. (ABP, 2012).

Throughout its 100-year history, port of Immingham handled about 1.7bn tonnes of cargo and created a significant number of jobs locally, regionally and nationally. “The port, which took six years to build, had been in operation since 15 May 1912 when the first commercial vessel docked” (BBC, 2012). The total combined export and import volume in the first year of operation was over 1 million tonnes. The Port’s popularity as a cruise hub significantly grew during the 1930s and during World War II when the Port was a naval base and headquarters for the Royal Navy’s Flag Officer for the Humber. The first roll on-roll off (ro-ro) berth was created in 1966, and in 2000 Humber International Terminal opened which has become one of the Port’s greatest success stories by meeting the needs of the shipping industry in the 21st century. In 2009, the refurbishment of a 23,000 m² storage facility at the

Immingham Bulk Park complex was completed, and Humber International Terminal handled its 70 millionth tonne - most of which have been coal imports for the UK's power stations (ABP, 2012).

Figure 34 The formal opening of the port of Immingham in 1912 (source: ABP, 2012).

The Port is located on the south bank of the busiest trading estuary in the UK, the Humber Estuary. The Port complex is the sixth-largest in Europe and is the pre-eminent facility on the Humber due to its natural advantage of deep water. With river and in-dock deep-water facilities, as well as easy access to the major trade routes, more than 260 rail freights are moved per week. On the other hand, because the port is linked with high-speed roads it facilitates UK-wide cargo distribution from a location strategically close to the UK's industrial hub. Figure 35 shows part of the Humber Estuary and the land use at port of Immingham (ABP, 2012).

In terms of commodity, the Port of Immingham offers an extensive range of roll-on/roll-off as well as lift-on/lift-off freight services (ABP, 2018). Commodity types vary from dry bulks, liquid bulks, and unitised cargo to other bulks. Dry bulk cargoes vary from those servicing the energy and industrial trade sectors (coals, ores, biomass etc.), to agribulks (grain, fertiliser, animal feeds etc.) as well as other bulk cargoes (road salt etc). Dry bulks and liquid bulks servicing the UK's energy and industrial sectors make up most of the cargo that transports through the Port. Humber International Terminals (HIT) 1 and 2 are capable of handling up to 20 million tonnes of coal each year. HIT handles solid fuel supplying power generators and can accommodate vessels carrying cargoes up to 130,000 tonnes. Stocks of coal are then distributed via rail to the power generators. HIT also handles large volumes of biomass, animal feed, road salt, and grain. Furthermore, liquid bulks are the largest commodity group (by tonnage) handled at UK ports. In 2010 they totalled 231.6 million tonnes, representing 46% of total traffic, of which crude oil and oil products accounted for 198 million tonnes. Over 25 per cent of the country's oil-refining capacity is located adjacent to the Port of Immingham and hence the port offers four specialist liquid-bulk terminals. In terms of unitised cargo or containers, with around 15 container vessel calls per week, Immingham Container Terminal is a regional centre for deep-sea container imports for significant volumes of commodity from the Far East. Furthermore, Immingham has eight roro berths (meaning roll-on/roll-off commodities such as cars and trucks), handling more than 30 sailings each week to/from Northern Europe and Scandinavia. Regarding steel, the port handles imports from countries around the world including Korea, China, and India and distributes Tata’s Steelworks products to worldwide destinations (ABP, 2018). Finally, general cargo, such as timber, steel aggregates, gypsum and minerals and project cargo (which cannot be categorised into dry bulks, liquid bulks or unitised cargo) are also handled at the port (ABP, 2012).

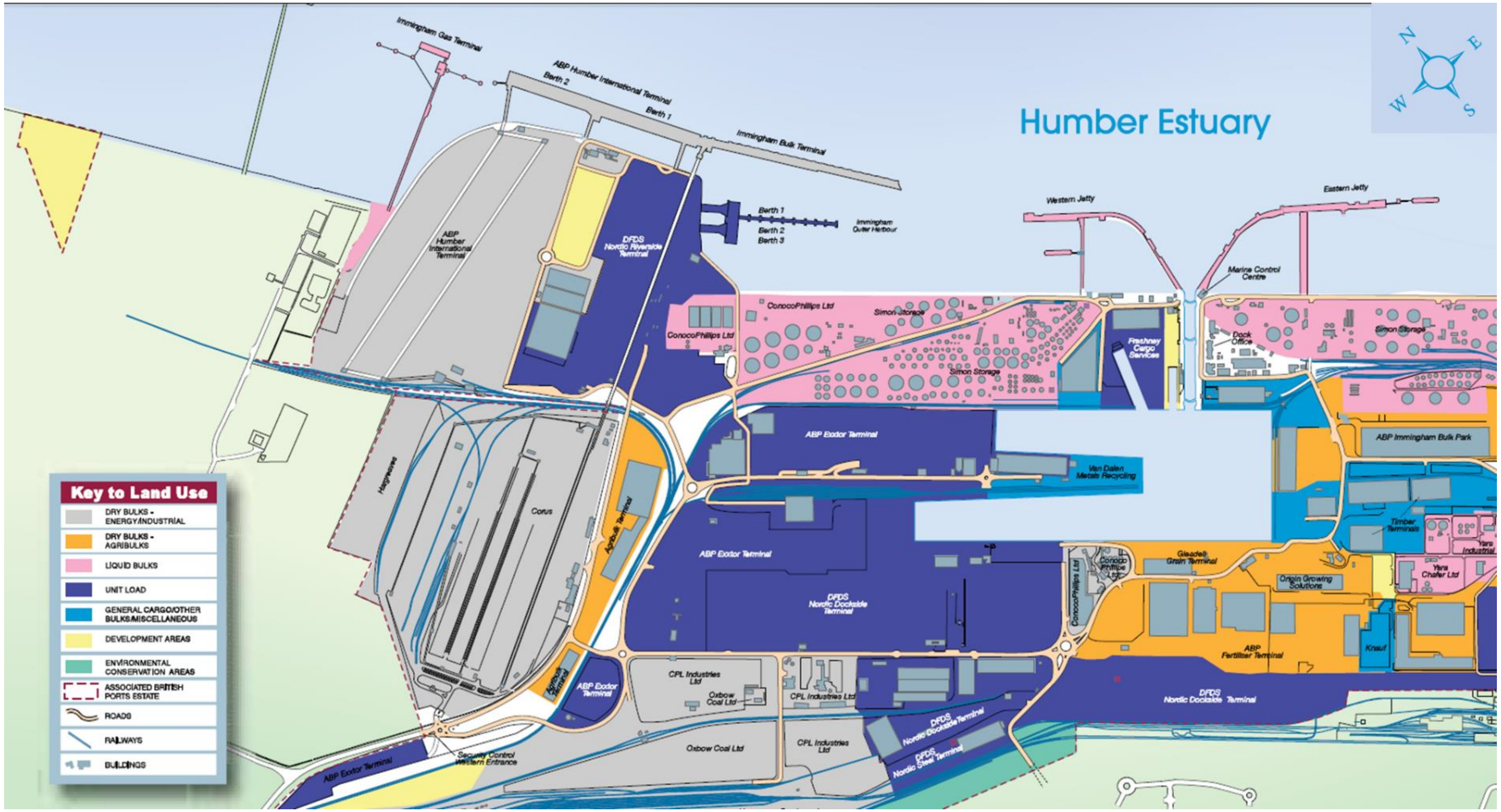


Figure 35 Land use at Port of Immingham in Humber Estuary (ABP, 2012)

4.4.2 The railways

Moreover, the freight route from/to the Port of Immingham in North Lincolnshire, UK, which is a major freight route connecting different infrastructures, including the port and the Electricity Supply Industry (ESI) (power stations in the area), was chosen for the case interdependency study. Although the route is regarded as a branch line for passenger traffic, it is also one of the major freight routes in the UK (Network Rail, 2013). Figure 36 shows the railway lines in the case study area together with the port, major cities and location of power stations. Interviews with experts showed that, while the route has strategic importance from the perspective of the national economy, little is known about the actual flow between infrastructure systems.

Figure 36 Case study area including the port of Immingham, Cities of Hull and Doncaster, Great Northern Railways and several power stations. Note that there are more power plants outside the boundary of the map. The figure was recreated from the diagrams of Rail Map Online (2019). The map was adapted from Google Map, under Google's policy on reuse and annotation of its maps.

Regarding the role of the railway, passenger transport services in the case study area are rather limited, however, it is busy with freight traffic with more than 2 paths per peak hour in one direction in 2011-12 (Network Rail, 2013). The stakeholder interviewed confirmed that the majority of the freight is coal and biomass for ESI, in addition to oil to inland oil terminals and other materials to steelworks.

Furthermore, regarding the railway infrastructure in the case study area, a closer look into the railway route (Figure 37) shows that after the freight traffic leaves Immingham port, it goes through Brocklesby junction and Barnetby station (Wrawby junction), and then to various destinations. Whilst there are alternative routes to the west of Barnetby station (i.e. if the section between Scunthorpe and Barnetby is closed, freight trains can be diverted through power stations), no alternative route exists for the section between Brocklesby junction and Barnetby station. This section is considered as a critical section/bottleneck along the route and causes vulnerability to the supply chain and the interdependent infrastructure system in the area. Thus, if any component within this section fails to operate as expected, it could result in the stopping of the supply chain. To properly investigate the components of this critical route, a site investigations and visit has been carried out for this research within the railway premises. The outcome of these investigations including the observations and information railway experts provided verbally during the visit were combined with further desk studies to find more details about the railway infrastructures at the case study area. It is found that the railway line within the section is not electrified and a traditional block signalling system is used for the section. This means that "signals are provided at fixed lineside locations to indicate to the driver of an approaching train how he should proceed or, possibly, the limit of his movement authority. To achieve this, the line is divided into sections, often called blocks, and a signal is placed at the entrance to each block to act as a sort of gate keeper" (Connor, 2017). According to the railway rules, normally only one train is allowed into a block at any one time. Network Rail is currently implementing the North Lincolnshire Signal Upgrade programme and upon completion, signals in the area will be controlled by a central signal control centre at York (except the signals at Immingham Port, which will be described later). Regarding the surrounding infrastructures, the Barnetby - Brocklesby section traverses gently undulating land. There is no major river requiring significant spans. However, there are several bridges at intersections with local roads. The railway stakeholders described these bridges and local culverts as critical, because a failure in any of these assets usually leads to an extended recovery term. Around half of the bridges are overbridges (where a road bridge is above the rail track). It is assumed that overbridges could be closed in the case of any sign of failure and therefore the railway could still operate. Thus, overbridges have not been considered as a major risk or concern for the case study. There are also some underbridges (where a rail bridge is above the road) which are listed in Figure 38. Note, the numbers shown on the figure indicate the mileages and chainages of the railway line which show the distance from the origin of the line (in this case Sheffield station that is not shown in the figure). For instance, 94.1100 shows 96 miles and 11 chains, where chain is a unit of length equal to 22 yards. There are some culverts for drainage, but at the time of the site visit in June 2015 none of them exhibited any water flow except one (94.1100) to the east of Barnetby junction. The status of the flow during wetter seasons is unknown. Figure 39, Figure 40, and Figure 41 show photos of Barnetby East (94.1352), Croxton (97.1304) and Croxton (98.0264) respectively. Note that during the site visit no bridge could be found around 98.0796 but instead a level crossing was seen (Figure 42). As there was a lot of vegetation, it might be the case that a small bridge is under the vegetation. In addition, as there is not enough safe clearance for the road under Croxton (98.0264), a sign encourages large vehicles to use a nearby level crossing (the right-side photo of Figure 41).

Figure 37 The critical section of the railway line in the case study area (annotated on Google Maps)

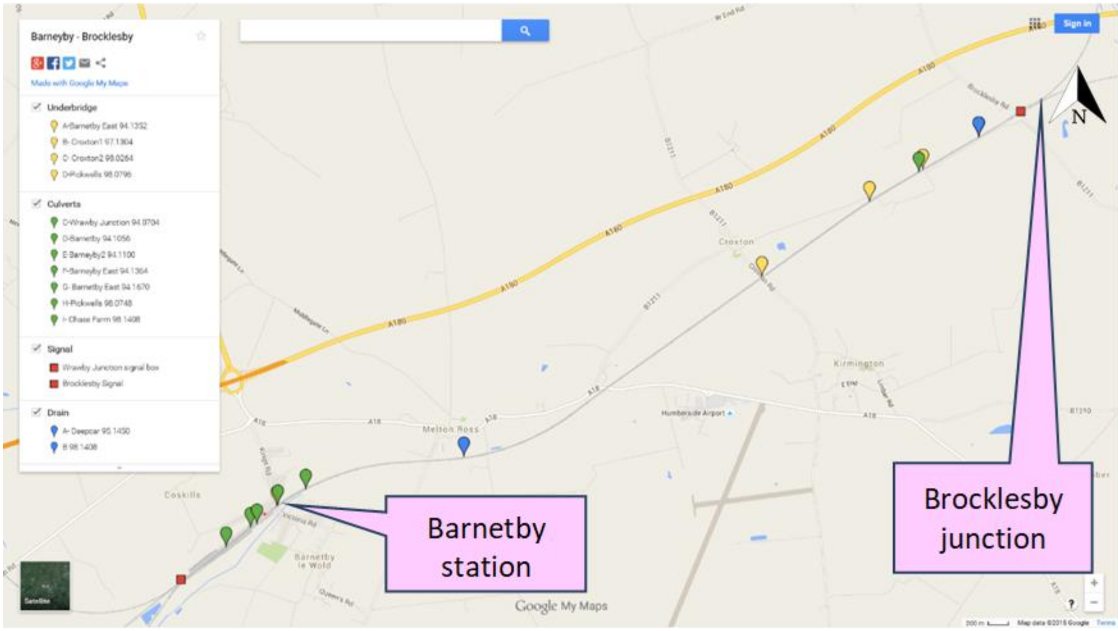


Figure 38 Bridges and culverts on the focussed section, NTS. Note that the figure was created to overlay the information given by Network Rail on Googlemap, 2015. The numbers in the legend mean the distance from the origin of the line.

Figure 39 Bridge: Barnetby East (94.1352) (the photos are taken during a site investigation)

Figure 40 Bridge: Croxton (97.1304) (the photos are taken during a site investigation)

Figure 41 Bridge: Croxton 2 (98.0264) (the photos are taken during a site investigation)

Figure 42 Level crossing around (98.0796) (the photos are taken during a site investigation)

4.4.3 Coal and biomass for the Energy Supply Industry

In addition to the role and the criticality of the railways, Immingham port is known as a major port for the import of coal and biomass for the Energy Supply Industry (ESI) in the UK. The data for the period from January to June 2015, extracted from UK Trade Info (2015) (published UK trade statistics data), was used to analyse the share of coal imports by port (Figure 43). Originally, the unit for the dataset is GBP (£). Because the value of the coal may have changed over the period, the amount-based share and value-based share data would be slightly different. However, it shows the current role of Immingham Port with regard to the volume of coal imports within the UK. Evidently Immingham is considered as the major coal import port and its share is 41%. All the coal imported at Immingham and transported by rail goes through the case study section.

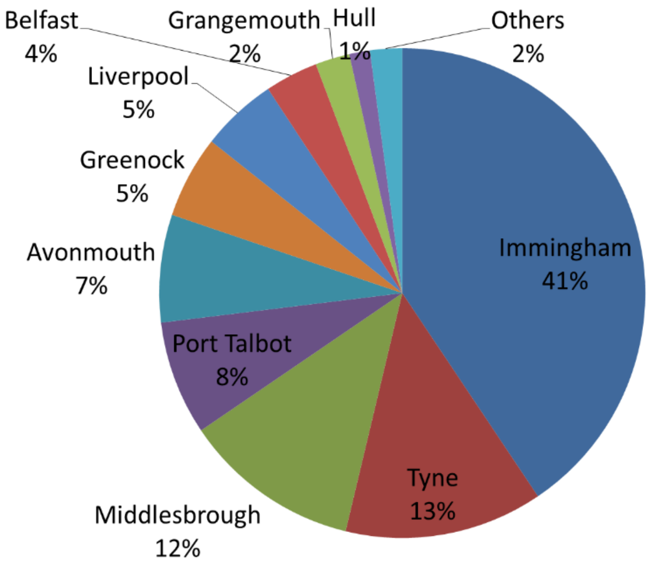


Figure 43 Share of coal import by port (January 2015 to June 2015, GBP (£)-based)

The share of the import of biomass was extracted from UK Trade Info (UK Custom data) and is shown in Figure 44. Note that the original unit for the dataset is GBP (£) and the value of the wood pellet may have changed over the period and thus the amount-based share would be slightly different from the value-based data.

Nevertheless, the figure provides a picture of how the importing of biomass into the UK depends on Immingham port as a major biomass import port with a share of 58.7%.

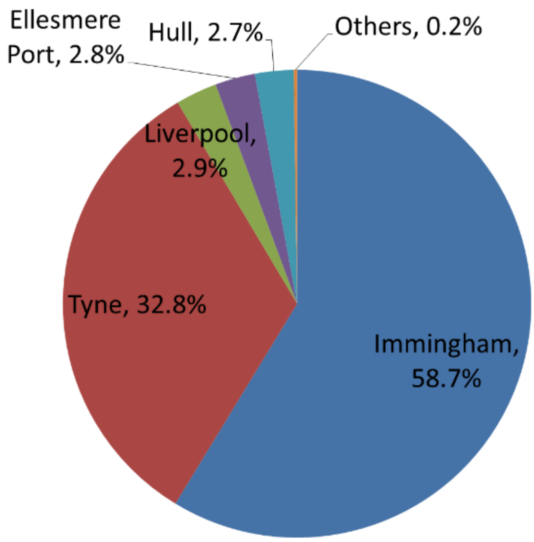


Figure 44 Share of biomass import by port (January 2015 to June 2015, GBP (£)-based)

Table 15 shows the major coal-fuelled power stations in the UK. The table is an extract of DECC (2015) and shows coal- or coal/biomass-fuelled stations that were operational at the end of May 2015 and have installed capacities of more than 1,000MW. In terms of the power station in the area of the case study, the shaded cells show those which use Immingham as an import port.

Table 15 Coal- or coal/biomass-fuelled power stations in the UK with installed capacities of more than 1000MW. Shaded cells indicate those which use Immingham as an import port.

Station Name	Fuel	Installed capacity (MW)	Location
Drax	Coal/biomass	3870	Yorkshire and the Humber
Longannet	Coal	2260	Scotland
West Burton	Coal	2012	East Midlands
Cottam	Coal	2008	East Midlands
Ratcliffe	Coal	2000	East Midlands
Fiddler’s Ferry	Coal/biomass	1961	North West
Eggborough	Coal	1960	Yorkshire and the Humber
Aberthaw B	Coal	1586	Wales
Rugeley	Coal	1006	West Midlands

Drax power station currently has the largest biomass-fuelled electricity generation capacity in the UK. According to DECC (2015), “there are currently only two power stations whose generation capacity is more than 1000MW and which use biomass, namely Drax and Fiddler’s Ferry (at Warrington)”.

To summarise, Immingham Port is a major player in terms of coal and biomass imports and all the commodities at the port are transported by freight railway. Also, Drax is a major coal-fuelled and biomass-fuelled power station in the UK. Hence, the freight railway connecting the port and the power station could provide a great example of the dependency between electricity power supply and freight railways. On the other hand, some infrastructure properties or components of railway systems in the area may potentially cause disruptions for the normal operation of systems. Therefore, not only does this case study provide a great example for the investigation of linkages between systems in a normal operating state, but this could also provide valuable insights into little-known dependencies related to railways and within the context of vulnerabilities.

4.5 Framework for analysis

This section outlines a framework that supports the analysis of a dependency between railway systems and an electricity generation system. Note, the framework explained in this case study is considered as a sub-framework to the generic one outlined in section 3.5. The generic framework can be used at a high level for investigating different infrastructure dependencies, whereas a sub-framework is needed to describe the chain of logic in analysing a local-level, case-specific, technical dependency for railways - such as the case in this chapter.

First, a schematic representation of the current situation regarding the infrastructure systems in the case study area is presented which is shown in Figure 45. The figure shows that (as previously discussed) at an organisational level, rail is the only transport mode in the area that moves commodity for the Electricity Supply Industry (ESI). Additionally, Drax is a major coal-fuelled and biomass-fuelled power station in the UK (generating more than 24% of the total energy produced by the UK power stations) and the government reports (e.g. DECC, 2013 and DECC, 2016) showed that bioenergy, including biomass, will be a key source of future energy in the UK. Hence, the business continuity of power stations in terms of commodity supply chain needs to be maintained. At an infrastructure level (as previously discussed in section 1.2 and Chapter 2), railways as Complex Adaptive Systems (CASs) include dependencies and vulnerabilities with regard to other infrastructure systems. Hence, the vulnerability and recoverability of the railway infrastructure in the case study area matters greatly, as the sole supplier of ESI. Furthermore, at a commodity flow level, ports (mostly port of Immingham) import and handle coal and biomass which is later transported by the freight railway to the power station (Drax) for electricity generation. The nature of such commodity flow causes variations in rail traffic as well as variations in the level of stock at the power station and in the electricity generation.

Note the schematic representation of the dependency scenario for this case study includes commodities which are a) storable (e.g. coal) and b) perishable (e.g. biomass). As the perishable commodity moved by rail requires particular attention, its variations and stock levels matter. In cases where such scenarios deal with the cost benefit analysis of electricity generation using these commodities, the problem could be framed as a traditional Newsvendor problem in operation research (which usually focuses on optimising the stock level) (e.g. Lau, 1997). However, the interest of this research is focused on a dependency which can cause a shortage of supply to electricity generation due to disruption of rail traffic. It is argued that in the current very dynamic environment of rail freight, the electricity selling price can be highly affected by such a dependency scenario. Hence any analysis of this dependency should consider the variance and stock level of the commodity that can potentially affect the electricity generation either in a positive (through stock availability) or negative manner (through stock shortage).

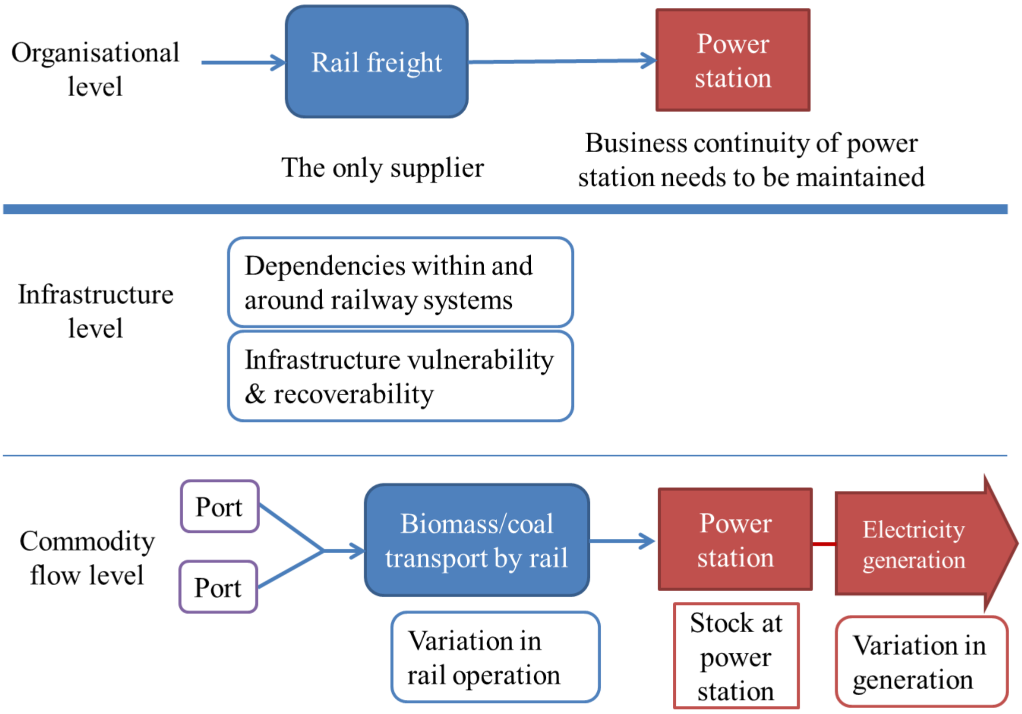


Figure 45 A schematic representation of the current situation of the infrastructure systems in the case study area

Acknowledging the current situation, the evaluation framework used for analysing the dependency between railway systems and other systems in the case study area is shown in Figure 46. The two columns shown in the figure resembles the two pillars shown in Figure 30 while the dependency evaluation is conducted at an infrastructure level as well as a commodity flow level. Information, concerns and needs are explored through engaging with experts in the area of the case study (which has been identified due to its strategic importance) and through the gradual and iterative process of scenario development. Regarding the infrastructures in the area at a high level, the overall dynamics between systems are characterised (in section 4.6) while at a higher resolution, also the vulnerabilities regarding disruptions of the commodity flow and the details such as stock and operational thresholds were identified (also in section 4.6). For the quantitative element of the research, data related to commodity movement (through rail traffic) and electricity generation were analysed to provide information regarding variation of commodity supply and electricity generation over time, their correlation, the stock level at the power station etc. (in section 4.7). As a result of such analyses, the general understanding of the dependency of electricity generation on commodity movement by railway traffic is improved while critical scenarios of such dependency are evaluated and quantified. The effectiveness and advantages of applying this evaluation framework for the investigation of a local/engineering dependency scenario is discussed in section 4.8.

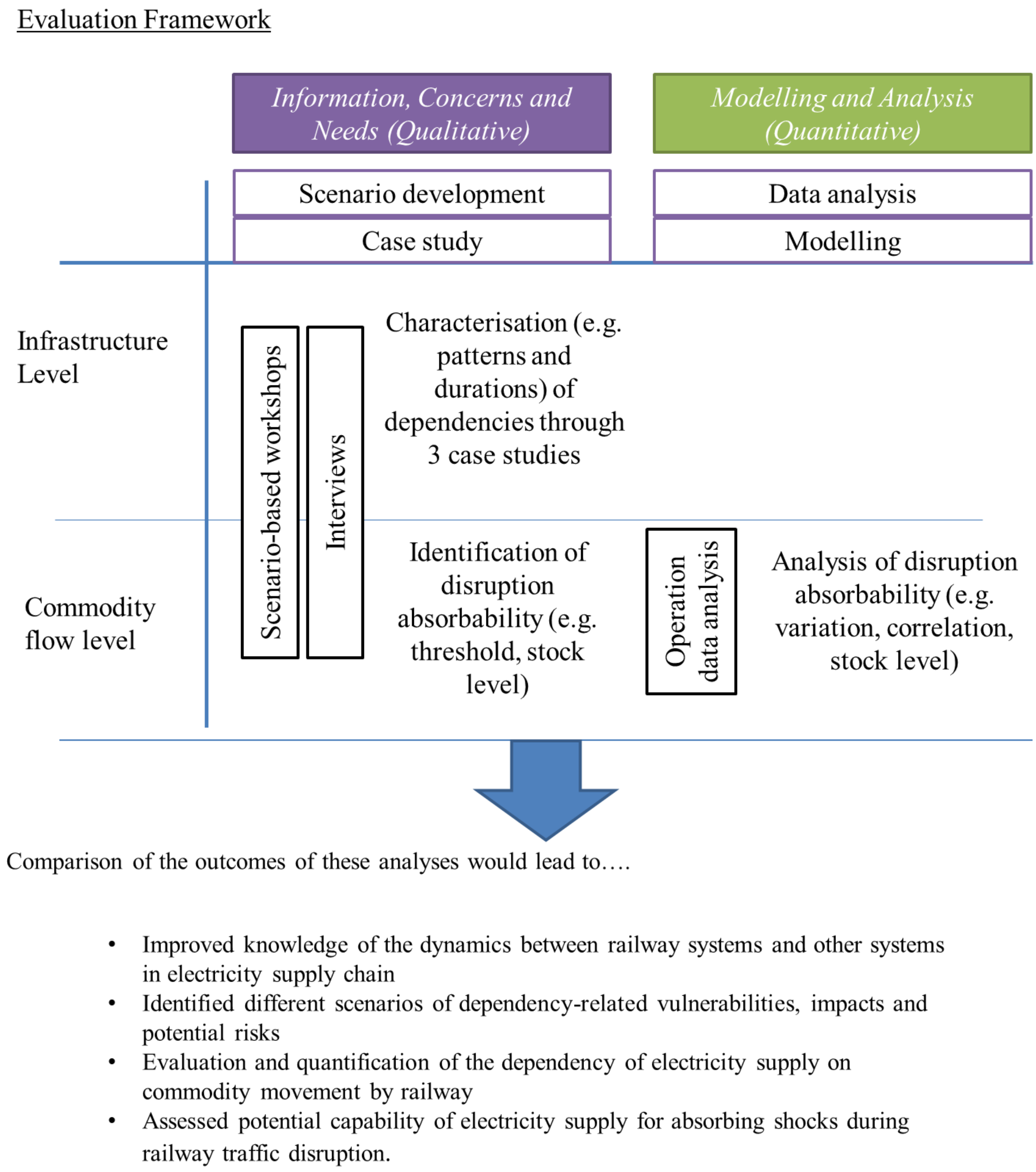


Figure 46 The evaluation framework for analysing infrastructure dependency between railway and other systems in the case study area

4.6 Qualitative investigation of dependencies in the case study area

This section summarises the outcome of a qualitative investigation into dependencies in the case study area. In order to better understand the potential dependencies that exist between three major infrastructure systems (port, railway and power) in the area, several interviews and a workshop were carried out. Several non-evident infrastructure dependencies (from both normal and vulnerability viewpoints) have been identified and summarised in this section. As explained in the framework of this chapter (section 4.1), a qualitative investigation supports an understanding of potential significant risks for the railway and the dependent systems in the area as well as understanding the details of the dependency scenarios such as the operational thresholds during disruptions.

The main reasons for carrying out a qualitative investigation using a participatory-based approach are summarised as follows:

- The nature of the infrastructure systems in the case study area (i.e. port, railway and energy supply) and the interactions between them are very complex. The information and data regarding the systems need to be collected from experts who are familiar with the daily operation of these infrastructure systems and the dynamics between them.
- As explained earlier (refer to Figure 30), to positively contribute to the academic knowledge of infrastructure dependency by generating quantified results and potentially developing decision making tools (e.g. for risk management), it is essential to first study and fully understand dependency scenarios at a case study level through collecting relevant information/data through experts.

The next section explains how information, concerns and gaps were effectively collected from experts who own, manage and operate the interconnected infrastructure systems in the case study area.

4.6.1 Interviews and the workshop

In total, 11 interviews with stakeholders (rail operators, power stations and the National Grid stakeholders) were conducted to understand their viewpoints on dependencies that exist in the case study area. Also, a workshop was run in the morning of August 17, 2015 in York, UK. In total, 18 participants from the rail and other relevant sectors, including energy and road traffic sectors, attended the workshop. The main reasons for the choice of a workshop and interview approach are that 1) some dependencies were not clearly known, and it was necessary first to identify and examine potential dependencies, and 2) although interviews helped as an initial step towards understanding the viewpoints and concerns of experts regarding dependencies, a workshop would allow us to obtain a consensus of opinions from a group of experts and local engineers. The following sections explain the details of the interviews and the workshop as the main methodology of a qualitative investigation for this case study.

4.6.1.1 Interviews

The purpose of conducting interviews was to firstly provide an overview of the current dynamics that exist between different systems and the potential disruptions (about which experts are more concerned about) by collecting knowledge from individuals. Such knowledge could not have been found from other sources such as the academic literature or publicly available sources (e.g. ABP, Network Rail and National Grid publications). Additionally, interviews were significantly helpful in recognising more key people for further investigations (participants in participatory modelling) which in this case resulted in holding a workshop. For instance, interviews with Network Rail and freight companies could reveal who the more relevant people to engage with are within both the railway sector and external organisations or sectors (e.g. Drax power station).

Regarding the key people who could be beneficial in contributing to the research, one important factor is to realize the common roles at different industries with regard to the topic under the academic investigation. For instance, since the topic of interdependencies between sectors could be potentially motivating for industrial practitioners from a resilience background, experts within this area at each sector could be more helpful for the purpose of participatory modelling. Additionally, the term resilience is better known as “business continuity” in practice among industrial experts, therefore, it is crucial to first, find “business continuity” experts at each sector and secondly, to communicate with them using concepts and terms they are familiar with or interested in. Furthermore, practitioners usually refer to what is known as interdependencies in normal operating conditions in the academic literature as the “flow” between sectors while “disruptions caused by external systems” is usually referred to what academic sources identify as interdependencies in a disrupted state of the infrastructures. This nevertheless indicates the importance of communication, specifically to find a common language between academic researchers and industrial practitioners during the process of participatory modelling.

Regarding the interviews with the railway sector and the rail freight and logistic company, the infrastructure manager at both Network Rail and Freightliner were interviewed. Interviewees at Network Rail included Project Engineers for infrastructure projects at London North Eastern and East Midlands, freight planning experts and customer relationship executives. Additionally, at the Freight Operating company (FOC) rail strategy and contract managers were interviewed mainly since the interactions between the infrastructure manager and FOCs affect the nature of the current traffic as well as vulnerabilities and disruptions. The elements comprising the main focus of these interviews are summarised as follows:

- Project engineers at Network Rail were interviewed about the railway’s recovery process and the factors that may affect a recovery after a disruption caused by external systems, the details of inspection and monitoring, recoverability of the route and relevant arrangements as well as temporary recovery options.
- Freight planning experts at Network Rail were interviewed about the criticality of the route under investigation and the critical components/assets (e.g. bridges, signals), types of available risk mitigations, the available risk assessment tools, consequences of disruptions for the infrastructure manager as well as communications during and after disruptions.
- Customer (FOCs) relationship executives at Network Rail were interviewed about current freight traffic, busiest time of the year in terms of freight traffic,

factors contributing to the dynamic nature of freight traffic, criticality of the railway route for the freight industry, signalling capacity, theoretical capacity/tonnage of each freight train, upgrade and renewal scheme/program, consequences of disruptions on freight traffic, potential diversion routes, potential improvement for path availability, contingency plans and priorities during a disruption as well as a mechanism of communication between port, rail and power sectors.

- Rail strategy and contract managers at Freightliner Heavy Haul were interviewed about the sustainability of freight traffic during disruptions, operational resources and their impact on recovery, threshold for duration of disruption, rail path allocation, number and quality of available paths, duration of loading and unloading as well as a communication mechanism for risks.

Regarding the interviews with experts at the port, heads of operations for the Ports of Grimsby and Immingham were interviewed. These stakeholders` were interviewed regarding the current rail freight traffic from the port, passenger rail traffic from the port, track layouts at and around the port, types of commodities and freight tonnage, types of freight rolling stocks in the area as well as details of different terminals to investigate the current flow between the three sectors. Furthermore, the interviews also focused on recent incidents/disruptions at the port, potential vulnerabilities of the current flow, duration of the recovery process, communication during and after a disruption, room for resilience improvement/business continuity as well as suggestions for any dependency-related scenario-based study. On the other hand, the head of resilience planning, maritime security and consequence management at Department for Transport (DfT) was interviewed about; potential environmental risks to the port, evaluation tools and methods to find impacts of disruptions on the supply of coal and biomass, rerouting of vessels at the port, options for improving resilience, standard procedures during a disruption and a communication mechanism between sectors.

Moreover, Logistic managers at Drax Power Station were interviewed to investigate the dependency of supply at Drax on railways and the port. These interviews focused on elements such as details about the units at the power station (e.g. number and capacity), factors affecting choice of ports, the size of coal and biomass stock at the power station, asset ownership issues (e.g. for wagons), types of wagons for different commodities as well as a communication mechanism between sectors.

To summarise, the interviews with the port, railways and power sector as well as DfT provided a better indication of the current dependencies that exist in the normal operating condition and within the context of vulnerability. Interviews with operational/planning/strategy managers helped build a picture of the current dynamics between sectors in the case study area at a relatively low-resolution level. Hence, a combination of local engineers/specialists and operational managers were invited to a workshop to collaboratively generate information regarding the vulnerability of the operation of the systems due to existing dependencies. The following section (4.6.1.2) explains the structure of the workshop held, followed by the overall findings of the qualitative investigation (by the site visits, the interviews and the workshop combined) in section 4.6.2.

4.6.1.2 The workshop

To ensure that holding a workshop helps meet the objectives of this research in an effective way, a structure was adapted including the following steps:

1. Introducing the background and the aim of the research as well as explaining the focus and general program of the workshop and introducing the participants
2. Introducing and explaining the predefined scenarios
3. Team working, group presentations and outcome collection

First, it was necessary to familiarise or remind participants of the overview of the research and the workshop they attended. During a 20-minute presentation, participants were reminded that this case study is part of a bigger academic project focused on the freight route from Immingham to the power stations in the area. The goal of the workshop was clarified as investigating the effect of potential disruptions on the operation of systems. The participants were also encouraged to brainstorm and develop some ideas regarding mitigation/alleviation options since such elements could motivate them to communicate more collaboratively and effectively. The program of the workshop which was run for 4 hours and 30 minutes (including breaks and a networking lunch) as well as the details of participants (e.g. names and organisations) were also introduced. A summary of the knowledge which was collected from public sources and at the interviews was presented, and finally the support of the interviewees and the workshop participants was acknowledged.

Next, since the workshop focused on the impact of disruptions, three predefined scenarios were introduced to the participants. The nature of the scenarios represented the vulnerabilities in the area which could be caused or aggravated by the linkages between systems. Additionally, the scenarios have been created considering the information found during the initial investigation phase (by desk study, site visits and interviews), such as the critical components in the area, concerns of stakeholders and the previous incidents. It should be noted that a scenario-based approach was chosen for this workshop because firstly, interviews revealed that experts are more concerned about the vulnerabilities which could result future disruptions that bare similarities to past incidents and that could more severely affect railway operations which connect the port and the power stations. Secondly, since the vulnerabilities of railways are very diverse due to the dependencies on the external systems, a significant amount of work would be required to discuss all dependencies and it would be impossible to conduct a dependency analysis on all likely scenarios in one workshop. Therefore, the workshop should only target key dependencies in the case study area which were previously discussed with the experts. Hence, based on the interviews and the previous desk studies, the following scenarios were created for discussion in the workshop:

A. Signal equipment failure in the port

B. Bridge strike caused by a diverted lorry

C. Failure of a geotechnical structure in the case study area

Prior to the workshop, details were added to these scenarios based on the findings to date in consultation with experts at interviews. The detailed scenario settings given to the workshop participants were as follows:

- Scenario A: Following the storm surge in December 2013, there was an extensive coastal inundation in the port area. The flood water severely damaged signal equipment along the line, including the signal control box at the Immingham Reception. These signalling facilities are Victorian and there were no drawings or replacement parts available (see Figure 47). As a result, there were no trains from Immingham port. Note that an overview of the environment around Immingham port and its susceptibility to flooding from river and sea is given in Appendix A. The exemplar demonstrates the use of freely available data to assess susceptibilities to flooding as an initiating event, resulting in a cascading failure between geographically dependent infrastructure systems.

Figure 47 Signal control box at Immingham reception

- Scenario B: Unprecedented cold weather and an icy road surface led to a lorry turning over at the junction of the A180 and A160, which caused multiple crashes on the A180. As a result, the A180 was closed between the Junction A180-A160 and Junction A180-A1136 including both junctions (see Figure 48 as well as Figure 36 and Figure 41). Because of this closure, lorries from Immingham Port were diverted to Ulceby, West End Road and the B1211. One lorry, which was driven by a foreign driver and was carrying chemicals, hit the spans of Croxton Bridge (97.1304) of the railway, and the spans were severely damaged/burnt. All three tracks were closed. Note that according to Network Rail (2017) which archived the records of reported bridge strikes, these incidents are very common, and they continue to be a significant risk to railway safety.

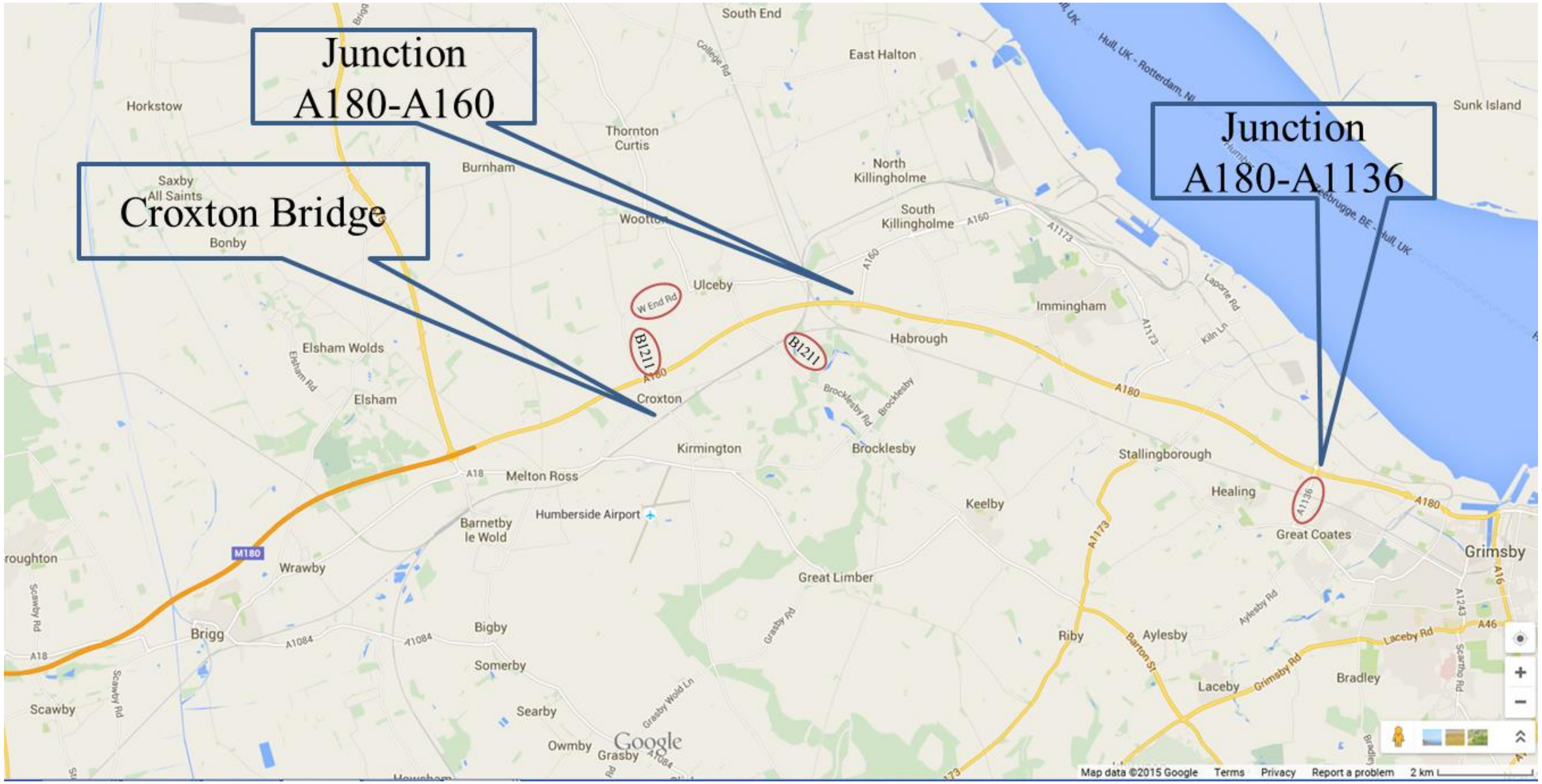


Figure 48 Scenario 2: Map around the critical section highlighting the following elements: A180, A1136, A160, B1211 and West End Road as well as the location of the Croxton bridge (source: Google Maps, 2018)

- Scenario C: Water mains passing under Kings' Road (Barnetby East (94.1352), near Barnetby Station (see Figure 38 and Figure 39) had been damaged over the years, resulting in leaking, which was invisible from the surface. Because the geology around the bridge is prone to 'running sand conditions' (note that the Barnetby-Brocklesby section is subject to several zones of category c 'running sand' hazard as highlighted in Appendix B), the exfiltration of mains water had gradually flushed supporting materials from around the bridge. Following a period of heavy rainfall, a hole appeared in the roadway adjacent to the bridge, alerting engineers to the hazard and enabling discovery of significant displacement of an abutment of the Kings Road Bridge. As a result, it was necessary to close the line. An overview of the environment near Barnetby Station is given in Appendix B, the exemplar demonstrates the use of geohazard to assess susceptibilities to ground stability issues including landslide and running sand ("Running sands" are materials that are sensitive to exfiltration and flushing). Note in 2015, in a similar incident, a huge hole appeared in one of Manchester's busiest city centre roads since rainwater weakened the soft sediment under the road. (Figure 49 has been shown during the scenario presentation to the participants to help their understanding).

Figure 49 A hole suddenly appeared in Manchester on 14 Aug 2015 (12m deep, 4.5m wide) source: BBC (2015)

After explaining the scenarios, each scenario was allocated to a group of participants to focus on (see Table 16, Table 17 and Table 18). The factors which influenced the grouping was based on the nature of the scenario as well as the sensible distribution of expertise in all three groups. For example, an expert from British Geological Survey (BGS) was present as a member of group 3 which focused on scenario C. Also, since railways is the main interest of the research as it played a key role in creating linkages between the sectors, a bigger number of railway stakeholders were invited. Moreover, in addition to three/four participants, one lead and one notetaker were also allocated in each group to ensure the process, the time and the outcome were managed efficiently. In terms of logistics, each group was provided with flipchart papers, as well as pens and post-it notes to facilitate the collection of the outcome. The groups were asked to discuss and produce an outcome regarding potential implications of the incident given in the scenario and the extent of the impact on railway traffic, including the duration of the closure of the railway line as well as knock on effects on other industries. The flipchart notes produced by all three groups are included in Appendix C. Two sessions of a 50-minute duration were allocated for the interactive communication of each group to produce results. During the second session, the participants were also encouraged to propose and develop options for mitigation/alleviation of impacts of disruption. A summary of proposed options/solutions are presented in Appendix D. However, since the solutions were not the primary focus of this research, the qualitative findings regarding the poorly known interdependencies between railways and other systems are explained in the following sections. Note that these findings, as the overall outcome of section 4.6, are a combination of all the knowledge gathered through engagement with stakeholders.

Table 16 The details of group 1 who produced an outcome for scenario A

Group	Participant	Organisation	System/Infrastructure	Expertise at the organisation	Role in the workshop
1	1	Network Rail	Railways	Business Continuity	Participant
	2	Network Rail	Railways	Freight Planning	Participant
	3	Network Rail	Railways	Signalling	Participant
	4	National Grid	Electricity	Resilience Specialist	Participant
	5	Arup	Research	Consultant	Lead/chair
	6	UCL	Research	Researcher	Note-taker

Table 17 The details of group 2 who produced an outcome for scenario B

Group	Participant	Organisation	System/Infrastructure	Expertise at the organisation	Role in the group
2	1	Network Rail	Railways	Business Continuity	Lead/chair
	2	Network Rail	Railways	Freight Planning	Participant
	3	Network Rail	Railways	Signalling	Participant
	4	Highway Agency	Road	Resilience Specialist	Participant
	5	Dudley Consulting	Research	Consultant	Notetaker

Table 18 The details of group 3 who produced an outcome for scenario C

Group	Participant	Organisation	System/Infrastructure	Expertise at the organisation	Role in the group
3	1	Network Rail	Railways	Business Continuity	Participant
	2	Network Rail	Railways	Structure	Participant
	3	Network Rail	Railways	Geotech	Participant
	4	John Dora Consulting	Research	Research	Lead
	5	Arup	Research	Research	Notetaker
	6	British Geographical Survey	Environment	Geology	Participant

4.6.2 Findings

As a result of desk studies, interviews and workshops with stakeholders as well as a site investigation, it is evident that the port and the freight railways supply commodities for power stations, oil and steelwork industries and the airports in the area. However, the approved non-evident infrastructure interdependencies (from both normal and vulnerability viewpoints) are categorised as follows.

4.6.2.1 Vulnerability due to routing and infrastructures of the railway

As previously mentioned in section 4.4, the map of the area, observations from the site visits and information provided by railway stakeholders showed that there is a critical section in the case study area between Barnetby and Brocklesby. During the interviews and the workshop, it is agreed that this section is considered as a critical section/bottleneck along the route and causes vulnerability to the supply chain and the interdependent infrastructure systems in the area. Thus, if any component within this section fails to operate as expected, it could result in the disruption of the supply chain.

4.6.2.2 Vulnerability of dependent systems due to environmental and climate-related aspects

Climate UK (2012) summarises the climate change risks to Yorkshire and Humber. The report suggests that flooding (including coastal flooding) is a major risk to the region (detailed information is attached in Appendix A). Figures and data from Risk of Flooding from Rivers and Sea dataset (Environment Agency, 2015), indicate that there is only limited scope for “moderate” risk of flooding for the critical section between Barnetby and Brocklesby (specifically located around small streams to the south west of Brocklesby Junction). However, there is a notable coastal-flooding risk around Immingham port. Climate UK (2012) also suggests increased temperature, storm/wind damage, and continuing snow and ice as climate change risks for the region. However, according to interviews, the stakeholders have chosen flooding as their primary concern in the first instance. It is argued that in a case of coastal flooding, if a terminal is damaged, it takes approximately 3 months for its repair.

The port and the dependent railway route supply not only coal/biomass for the Energy Supply Industry (power stations) but also oil for other sectors (including aviation) as well as resources for Tata's Steelworks at Scunthorpe. This means that different industrial sectors would be affected by disruptions and further work is required to understand these effects. Regarding actual incidents in the past: on December 5th, 2013, England's east coast between the Humber and the Wash experienced flooding from the most serious tidal surge in 60 years. Around 7,000 hectares of land flooded with major impacts at Immingham port (Environment Agency, 2014). The port of Immingham closed for 7 days and the damage to critical infrastructure at the port caused several weeks of disruption to the vital supply chain in the area.

In addition to flooding incidents, heavy rainfall can be a cause of secondary impacts. The landslide at Hatfield Colliery (around 50km west of the focussed section) in 2013 was caused by a period of heavy and accumulating rainfall, destabilising the colliery spoil that had accumulated over (possibly weak) alluvial soils immediately adjacent to the track. The slip formed as a rotational and translation displacement as the spoil slopes failed (under the added weight of water), the slip migrated off the spoil, with the rotational failure plane and toe of the slide deforming the rail tracks. Participants in the workshop discussed that this was a combined anthropogenic/weather event and critical factors included the proximity of the spoil (and its design), the weather loading and the distance over which the failure occurred. The Scunthorpe-Doncaster line was closed for 6 months, requiring a significant diversionary route. This is on the main route from Immingham to Drax and other power stations with lines for diversion. However, this could clearly indicate that the railway line can potentially be closed for a long time and hence the dependent supply chain (e.g. biomass) could be affected.

4.6.2.3 Vulnerability of systems due to asset ownership issues

There are assets technically used by an infrastructure which are legally owned by another infrastructure (e.g. Figure 50). Several railway assets, including tracks and signals, are owned by the port (Association of British Ports (ABP), Immingham) because they are geographically within the port premises. Although the section in and around the port is one of the busiest freight routes in the UK, the signal equipment that supports the operation is old due to the asset ownership issue. Network Rail's infrastructure improvement work and upgrade programmes cannot cover the signalling assets within the port. Interviewees and participants in the workshop discussed that some of this equipment is Victorian and there are no drawings of replacement parts available. There is no company which supplies spare parts for the equipment. The equipment is old, and currently replacement parts come from another disused signal box in the port, but the number of parts is thus limited and is expected to run out at some stage. Moreover, because this equipment is located in the area of the port, large-scale flooding around the Port of Immingham may damage the railway signal box at Immingham Port sidings.

Figure 50 Equipment inside signal box at Immingham port

4.6.2.4 Dependencies related to people (staff and customers)

Interviewees and participants in the workshop discussed that staff (human resources) of one infrastructure are customers of other infrastructures. For example, port and railway staff (e.g. train drivers and maintenance engineers) usually use road transport to travel to work. It is commonly observed that services are disrupted/delayed due to staff shortages, especially in scenarios such as road congestion.

On the other hand, customers of one infrastructure are customers of another infrastructure using the same types of service (e.g. travel). It is important to note that a passenger uses different modes of transport to complete a journey. Therefore, assuring the resilience of one transport mode (e.g. railway) cannot guarantee a customer’s satisfaction. Customers may be moved to destinations where there would be no further means of transport (e.g. if the bus network is disrupted).

In another potential scenario, customers of one infrastructure may cause damage to another infrastructure. Railway bridge strikes by trucks diverted from their main/original route (due to a disruption, and possibly misdirected by satellite navigation) have been frequently observed (Network Rail, 2012 and Network Rail, 2017). Note that diversions of routes usually happen as a response to a main motorway closure which could be due to unexpected conditions (e.g. flooding at the port and adjacent roads). This is another example of a cascade of failure between infrastructure systems and their vulnerability due to dependency.

4.6.2.5 Dependencies related to inspection and monitoring of infrastructures

The operation of one infrastructure depends on inspection/monitoring of another infrastructure. For example, there are assets inside or within the boundary of railway premises such as utilities (water mains, gas pipes etc.) managed by different companies. Frequent inspection and monitoring of these assets may decrease the likelihood of incidents in railway premises (water main or gas pipe burst, etc.).

4.6.2.6 Dependencies during emergency and recovery conditions

An infrastructure system relies on other infrastructure systems in emergency situations. For example, in order to run freight trains with a restricted capacity, it may be possible to replace rail freight partly with road freight or replace local passenger traffic with a bus service. However, because each coal or biomass freight train carries around 1,600 tonnes of coal or biomass, such a replacement would cause heavy congestion on the road network in the area and would have various adverse impacts including delays in the journeys of local commuters or blocked access to the port for other port users (e.g. trucks which use ferry services). Also, as a result of flooding and interrupted services, trains may be suspended at stabling locations around the network. Normally these stabling locations are at the premises of power plants where trains can stop. Another minor example is that if a freight train driver runs out of working hours at a port siding in a disruption situation, a replacement driver will need to reach the location by car (using a road).

Furthermore, recovery of one infrastructure depends on cooperation and/or interruption in the operation of another infrastructure. For example, if a rail asset at an intersection with other infrastructures (road, water) fails, the fastest way to repair the rail asset would be to stop the service of the other infrastructures (e.g. by road closure, turning off water supplies). This would affect the users of that infrastructure. It was agreed that a recovery operation may adversely affect the users of other relevant infrastructure and that coordination is required. In some cases, it would be a challenge to gather professionals from different sectors to recover systems (e.g. in case of major flooding in the area of the case study).

4.6.2.7 Vulnerabilities in the long term (gradual changes)

Long-term operation of one infrastructure damages the assets of another infrastructure. For example, it was discussed that track tamping (a maintenance activity) as well as the current from track circuits (a signalling asset) damage nearby underground utilities.

Also note that assets within boundaries of different infrastructure systems interact. For example, assume scenario C of the workshop as previously explained: a water main passing under a road near the critical section of the railway had been damaged over the years, which resulted in leakage (which was invisible from the surface). Gradually the leaked water moved soil around the bridges, and eventually, when there was a heavy rainfall, a hole appeared around the bridge. This caused a displacement of an abutment of the bridge. As a result, it was necessary to close the line. Note that the prior stakeholder interviews identified ground water movements as a potential climate-change risk to geotechnical structures. As for this scenario, the initiating event appears as a gradual change (groundwater level change in the long-time scale) at the interface of railway, road and water assets. It was discussed that this type of incident is not limited to water. There are high pressure gas mains and oil pipelines across the railway. All have different standards, policies and owners. On the planning side, every infrastructure owner needs to understand the connectivity of their networks to other types of infrastructures. It would be ideal to share the data. Note that as no infrastructure owner has a perfect dataset, there should be a means whereby if data regarding the assets of another infrastructure owner is found to be wrong, this can be reported to the owner.

4.6.2.8 Dependencies due to the type of stock in the supply chain

The stakeholder interviews confirmed that the majority of the freight is coal and biomass for ESI, in addition to oil to inland oil terminals and other materials to steelworks. Stakeholders agreed that the case study area is a main transport corridor of coal and biomass to power stations. Currently there is no alternative for the critical section of the route. Also, the stock of biomass at power stations is smaller compared to the stock of coal due to the fact that biomass cannot be stored for longer than a week or ten days (i.e. the power plant usually stores an equivalent of one week of biomass stock). Note that considering the growth of biomass and other renewable sources of energy in the future, the national power supply can potentially become more vulnerable to disruptions in the supply chain. Furthermore, freight traffic in the area is dynamic and this adds to the complexity of the interactions between different sectors (port, railway and power plants). Considering these challenges, a better awareness of the dependency between freight railway and power production is necessary.

Note that the past incidents in the area of the case study (e.g. storm surge flooding at the port and Hatfield Colliery landslip) indicate that the supply chain (e.g. for biomass) could be disrupted. Additionally, on July 15th, 2014, a derailment at Brocklesby junction closed the railway line for 7 days, which is another local example of how a railway line could be closed (Davesrailpics, 2014). Local past incidents such as this, as well as other possible scenarios (as mentioned in the workshop) could potentially act as a vulnerability to dependent systems. Hence, it is important to further evaluate the dependencies that exist.

The next section evaluates the dependencies that exist between coal transport as well as biomass transport and power production at Drax power station. The main goal is to compare the degree of dependency due to the type of stock in the supply chain by analysing the data related to sectors.

4.7 Evaluation of an existing dependency: a quantitative analysis

As previously mentioned, the Energy Supply Industry (ESI) through power stations depends on the railway system in terms of a frequent supply of commodity. However, currently no study has investigated this dependency quantitatively. It is unknown whether it is possible to evaluate the qualitative dependency that stakeholders stated (mentioned above) using the available data related to sectors. Hence, this section used the data from power stations and railway traffic to evaluate a dependency that exists between the two infrastructures. First, the relevant data is collected from available sources and later analysed in order to investigate the connection that exists between the movement of freight by railway and power production.

4.7.1 Database

Power production data at Drax (subdivided according to the type of the commodity) and the total National Grid electricity production have been collected from https://www.elexonportal.co.uk/ (a site that provides operational balancing and settlement code data for electricity in Great Britain) and used for the analysis. The collected data shows the details required for dependency analysis including the quantity of electricity generated at each unit of Drax every day.

Train movement TRUST data of Network Rail has been used as a source to understand the real-time traffic. TRUST or Train Running Under System TOPS – Total Operations Processing System is a Network Rail computer system, which records details of train operational data as compared with schedule, supporting the logging of delays and associated attribution process (Network Rail, 2016). University College London collected the relevant TRUST data on an online dataset system called University College London's Freight Train Movement Data System (FTDMS) which is available at:

http://cege-ttrig.ad.ucl.ac.uk/trig/search/index.html

The dataset system enables access to details and past records. This dataset could be used to understand the actual number of freight trains, their destinations and other details in the past. The dataset can provide information about the amount of commodity supply to the power stations from each port during a year and the frequent travel paths for freight trains.

The TRUST (Train Running Under System TOPS) is a Network Rail computer system used for monitoring the progress of trains and for tracking delays on Great Britain's rail network. Whenever a train arrives, departs or passes by a reference point (that is a station or junction), it generates a report that contains the train's ID, the reference point's ID, and the scheduled and actual times of the arrival, departure or passing of the train. By collecting and organising reports, it is possible to create the movement history of the train. This dataset has a potential for the analysis of freight through ports because rail is the inland transporter of much freight from/to ports: one in four containers entering the UK is moved by rail; the majority of coal imported for power generation is transported by rail. It is expected that biomass for power generation has a similar trend to coal. Note that while the TRUST system generates reports on all the trains, UCL FTDMS captures the reports on freight trains only. The UCL FTDMS system allows viewers to see:

- Detailed movements of each freight train, which would help them understand the efficiency and reliability (i.e. duration of transport, delay, etc) of rail freight transport from/to ports
- Summaries of rail freight movements from/to ports, which include the destinations and the volumes as well as commodity types

It should be noted that both datasets available provide anecdotal but actual information about the freight train movements from port to power station.

4.7.2 Data analysis

Data of Drax includes "Unit ID" or "Asset ID" which according to Drax static data (available at: http://www.draxpower-remit.com/StaticData) reflects the fuel type at each unit. Accordingly, as Table 19 shows Unit IDs represent the following:

Table 19 The details of Drax's generating units. The fuel defines the primary fuel used for firing each unit

Drax Unit	Asset ID	Capacity (MW)	Fuel	Location
Unit 1	T_DRAXX-1	660	Biomass	England
Unit 2	T_DRAXX-2	645	Biomass	England
Unit 3	T_DRAXX-3	645	Biomass	England
Unit 4	T_DRAXX-4	615	Fossil Hard Coal	England
Unit 5	T_DRAXX-5	645	Fossil Hard Coal	England
Unit 6	T_DRAXX-6	645	Fossil Hard Coal	England

The data between 01/01/2017 and 17/12/2018 which are presented in 200,000 rows gives the quantity of power produced by each date (daily) and unit ID (fuel type). To extract the significant data, the total of the power produced per day has been calculated using the pivot table feature in Excel.

Furthermore, the train movement data extracted from FTDMS includes the following information which enables an understanding of the quantities of commodities transported to/from Drax power station:

- Train ID or train UID: Unique identification code for each train
- Current station: indicating the station/siding at which the data were collected
- Arrival time and departure time from the relevant siding (Drax power station in this case)

- From and to: indicating the movements of trains at the relevant siding (Drax power station in this case) hence showing where the train came from and where it is heading to. According to interviews with stakeholders, if trains are from "Immingham biomass terminal" or "Hull biomass" their commodity would be biomass and if they are from "Immingham Humber import terminal" their commodity would be coal.
- Timing load (railway term): total weight of the train (gross weight) which is technically equivalent to the sum of the net weight (the weight of the goods carried) and tare weight (weight of empty containers). This can help in understanding whether a train is travelling empty or full and hence whether it is transporting a commodity or not. Note that stakeholders' interviews showed that the weight of empty trains equals 800 tonnes while the weight of full trains (carrying any commodity) equals 2400 tonnes.

Moreover, the train movement data has been cross-checked. This means that to ensure that the data at one siding or station has been captured correctly in the database (on both TRUST data of Network Rail and FTDMS), the data at Drax power station was compared to the data at Ulceby and a number of other stations/sidings. This is to ensure that, for example, a train which is shown as "arrived at Drax power station" from "Immingham biomass terminal" in fact passed Ulceby station near to that time, which would be the only possible route for freight movement. Furthermore, there are irregularities in the data such as trains from Unknown departure to Drax. This information can be found out by cross-checking the data of the same day and around the same time in junctions before Drax or after Immingham and also by using common sense.

4.7.3 Results

This section demonstrates the variability of the commodity movement (based on the railway traffic) to Drax and the associated electricity generation. As explained earlier in section 4.1, such analyses can potentially support the future assessment of the capability of the power station in absorbing shocks for the scenario of rail traffic disruption.

In total, 2.1E+07 MW of biomass-fuelled electricity and 1.2E+07 MW of coal-fuelled electricity was generated at Drax in 2017. For 2018, 2.2 E+07 MW of biomass-fuelled electricity and 9.2 E+06 of coal-fuelled electricity was generated.

Figure 51 and Figure 52 show the monthly coal commodity tonnage (Tonne) and coal-fuelled power generation for 2017.

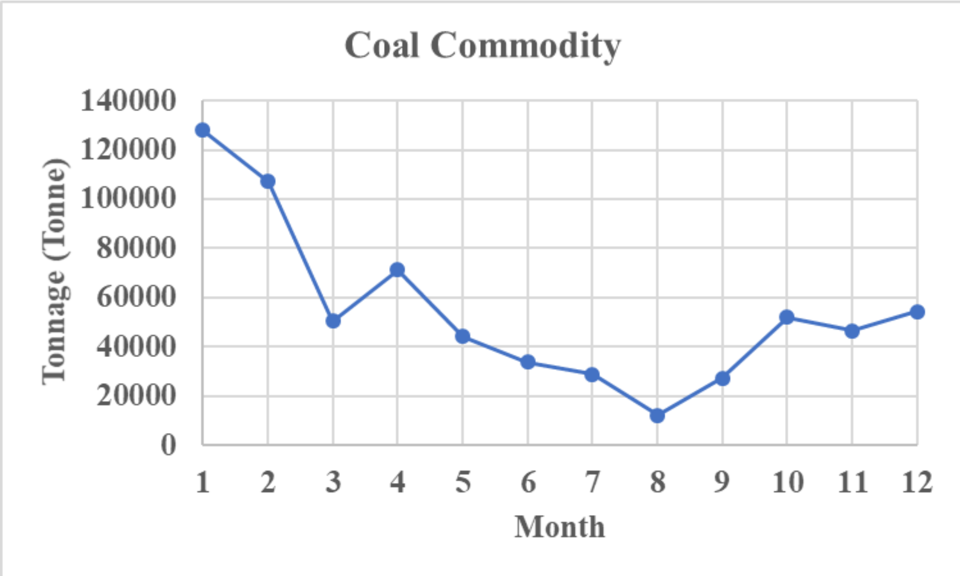


Figure 51 Coal commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (monthly basis)

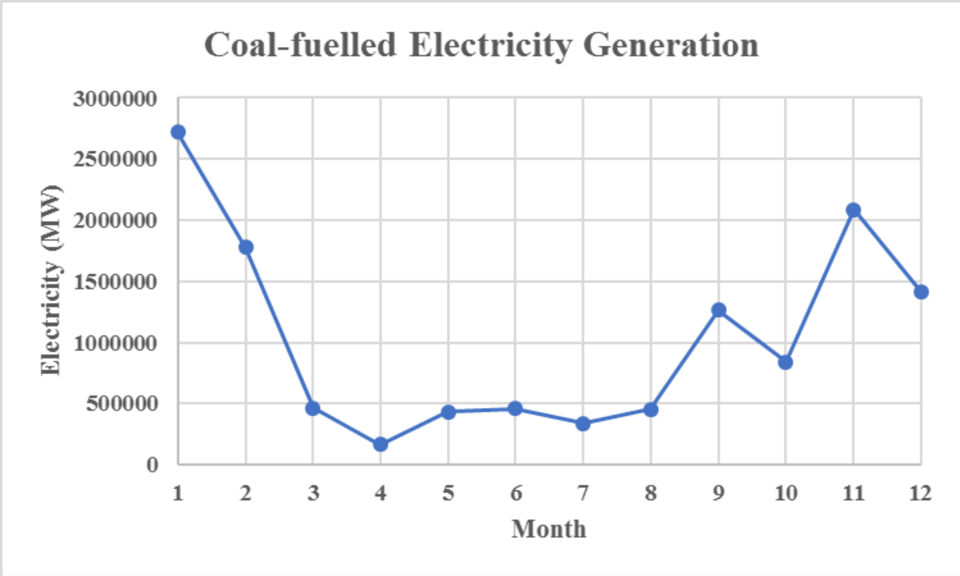


Figure 52 Coal-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (monthly basis)

The results show that the monthly-basis production data for coal does not express the same trend as the commodity. This means, for instance, when the coal commodity decreased/increased, the generation has not necessarily followed the same trend. However, as for the biomass, Figure 53 and Figure 54 clearly show a similarity for the trend of the monthly-based commodity supply and power generation.

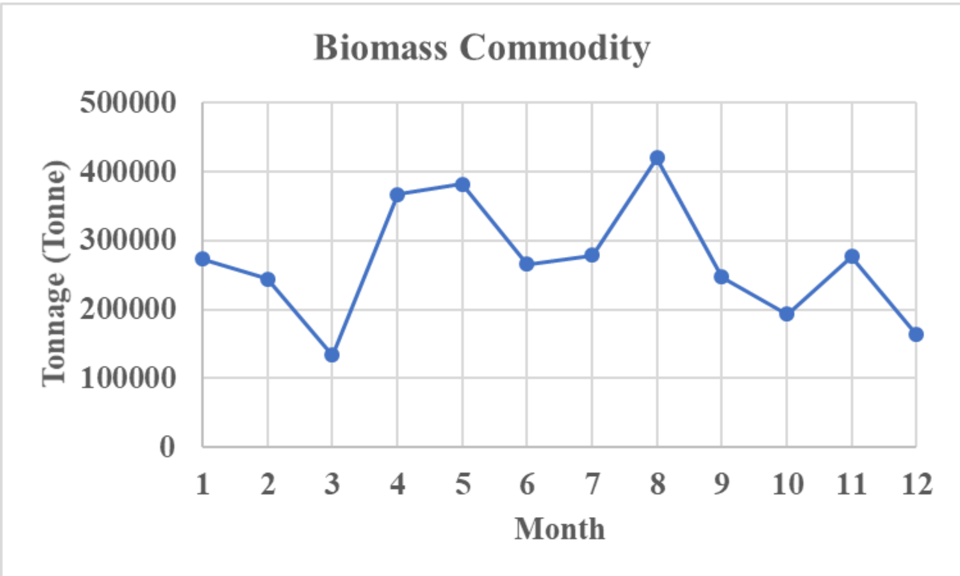


Figure 53 Biomass commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (monthly basis)

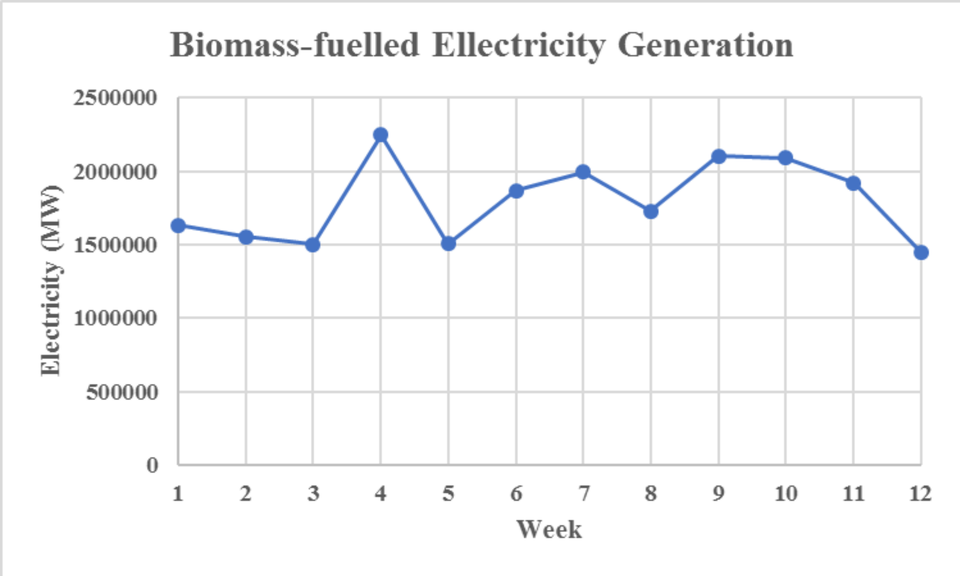


Figure 54 Biomass-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (monthly basis)

This indicates that when the commodity supply of biomass increases/decreases, the power generation also increases/decreases accordingly. However, a lag of about one month is observed between the extrema of the two graphs. This may be explained by the lag that in the reality exists between when the commodity arrives at the power plants and/or when the electricity associated with the commodity is generated and recorded in the dataset.

In terms of weekly data, Figure 55 and Figure 56 shows the weekly supply of coal and the associated electricity generation in 2017. Figure 57 and Figure 58 show the weekly supply of biomass and the corresponding electricity generation. Like the monthly-based data, there is a similar trend between the supply of biomass and the electricity generation. However, this trend is not obvious in the case of coal.

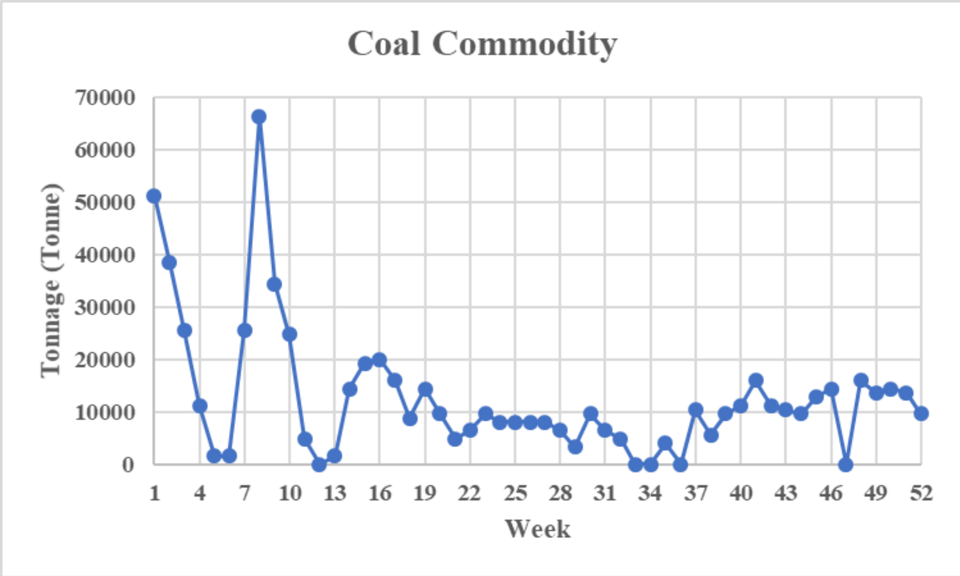


Figure 55 Coal commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (weekly basis)

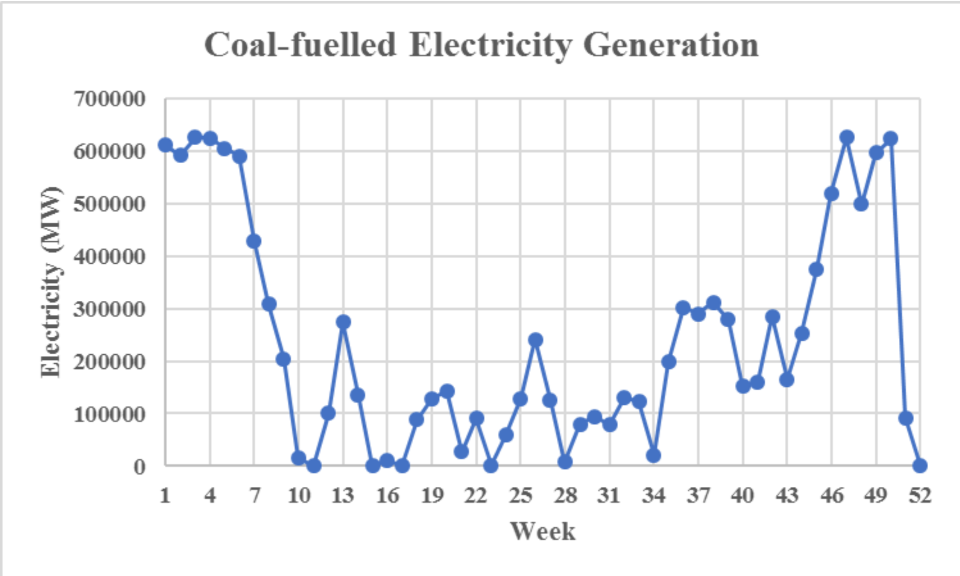


Figure 56 Coal-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (weekly basis)

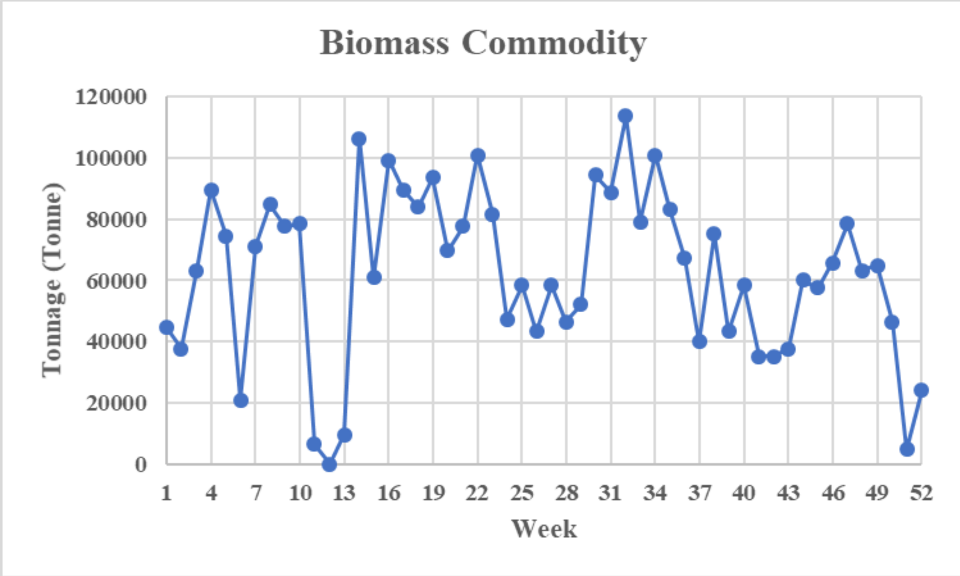


Figure 57 Biomass commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (weekly basis)

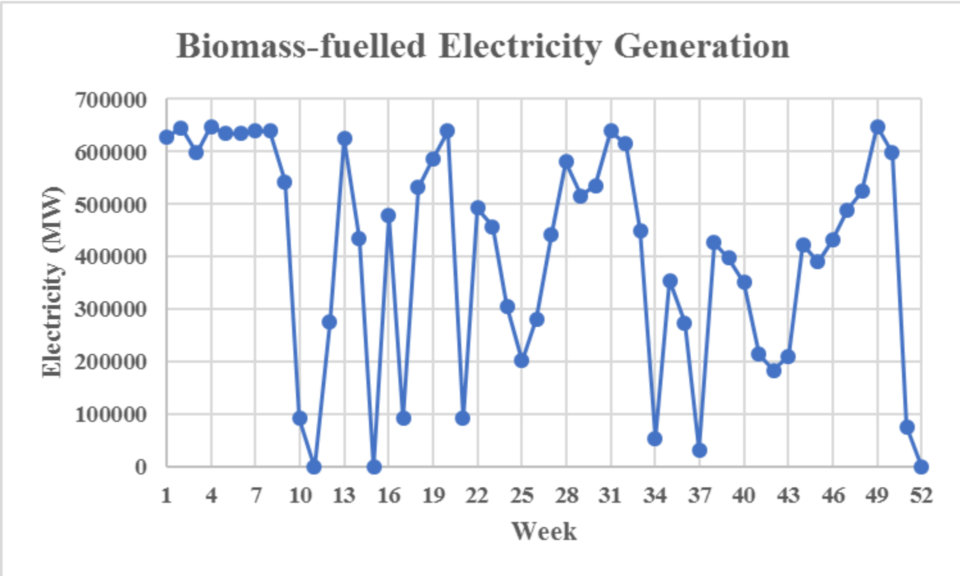


Figure 58 Biomass-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (weekly basis)

Figure 59, Figure 60, Figure 61 and Figure 62 show the corresponding monthly data for coal and biomass, respectively, for 2018. The data for coal underpins the analysis for the data of 2017: that there is no clear tight dependency between the coal-fuelled power generation and the coal commodity supply. The supply of coal was only during January and April. However, the electricity generation continued over the year. This indicates that there was enough coal stock at the power plant to cover the power generation for the entire year although the supply (by rail) was limited. Also, there is a possibility that in order to diversify the pot of supply, Drax used coal transported from other terminals. However, as far as the railway movement data showed, no coal commodity was observed to be transported to the power plant (regardless of the port of import). Furthermore, for the biomass, the trend between commodity supply and power generation is like that of 2017's.

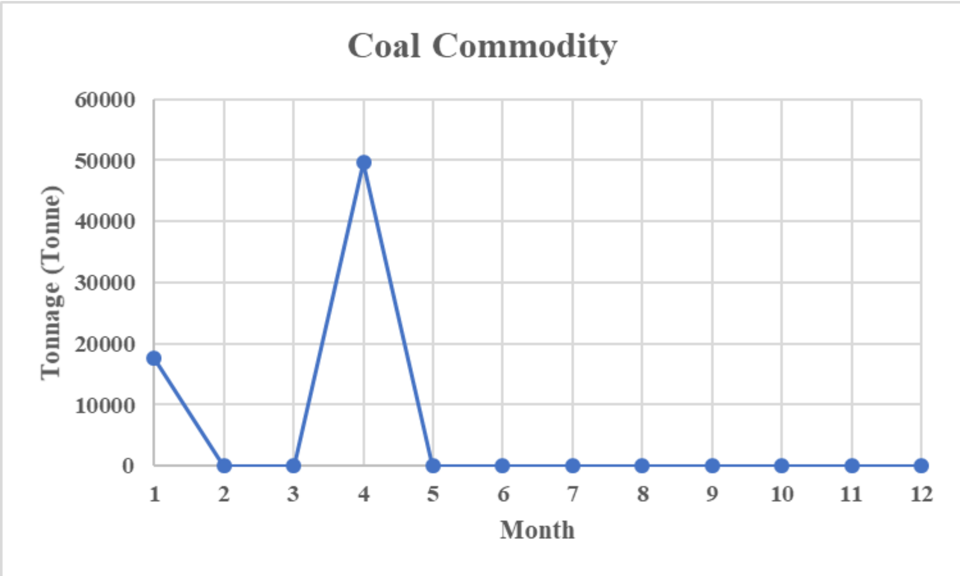


Figure 59 Coal commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (monthly basis)

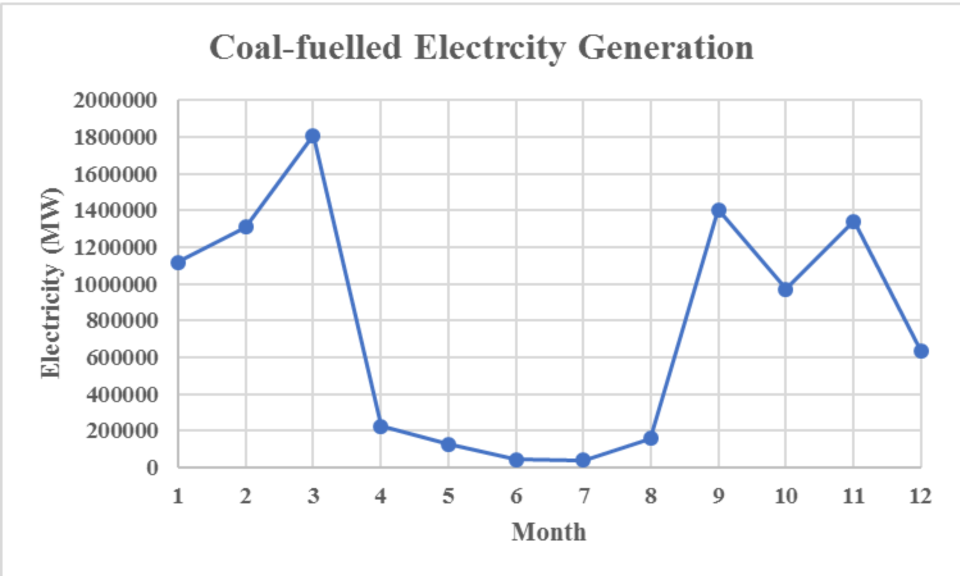


Figure 60 Coal-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (monthly basis)

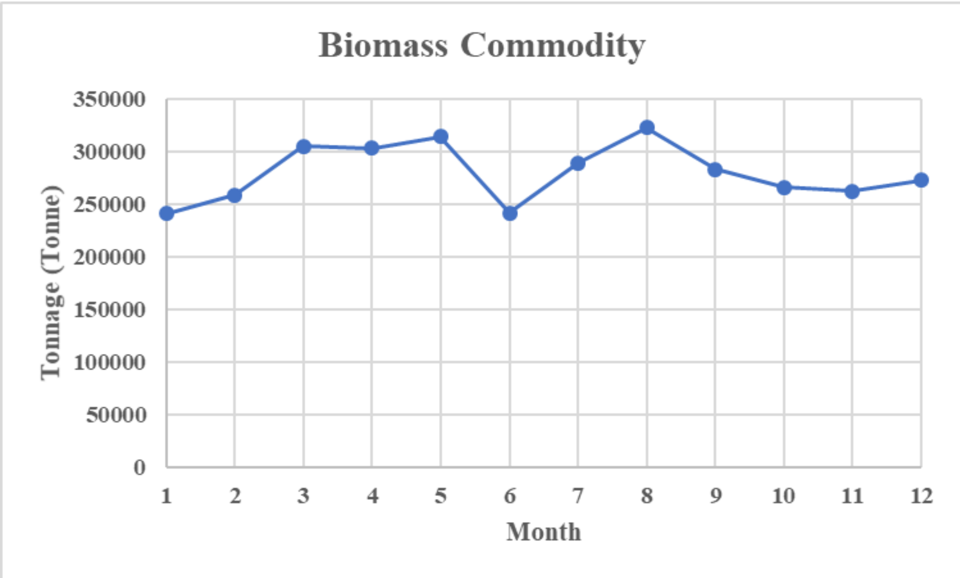


Figure 61 Biomass commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (monthly basis)

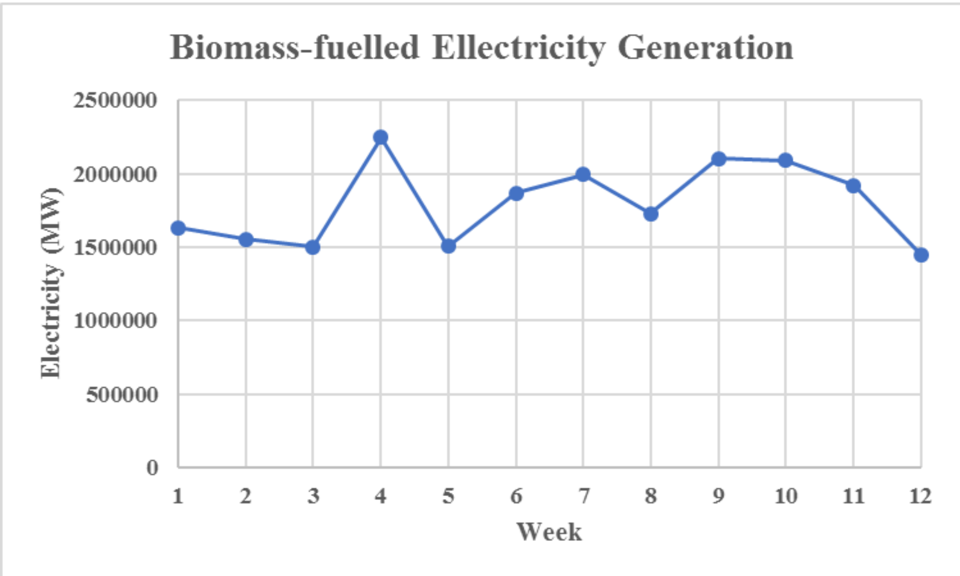


Figure 62 Biomass-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (monthly basis)

The weekly data for 2018 is shown in Figure 63 to Figure 66 for coal commodity and power generation and biomass commodity and power generation, respectively.

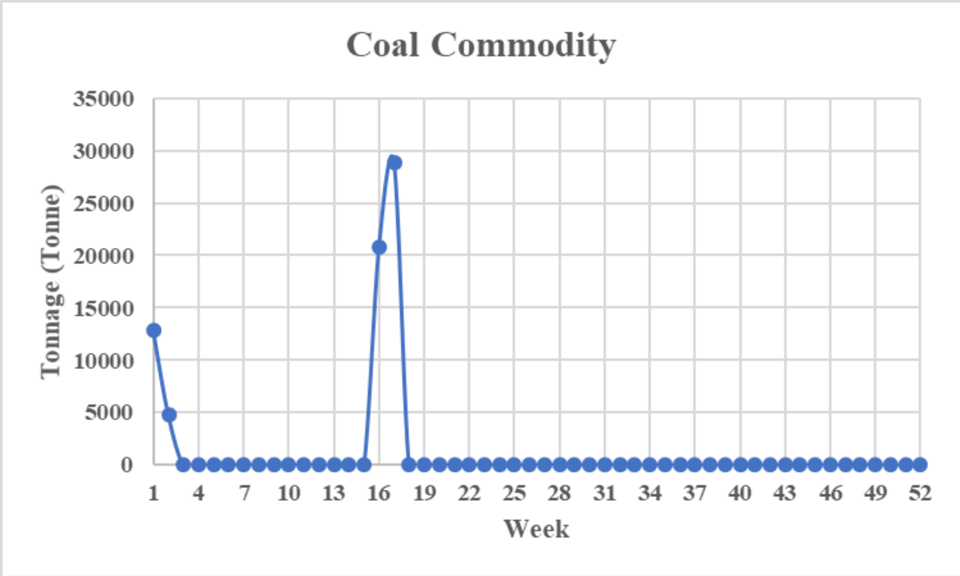


Figure 63 Coal commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (weekly basis)

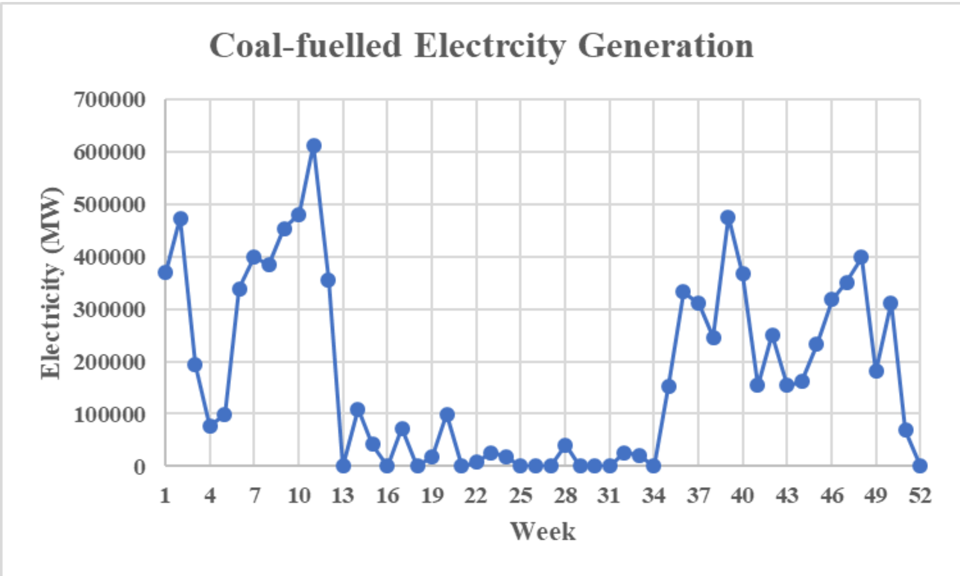


Figure 64 Coal-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (weekly basis)

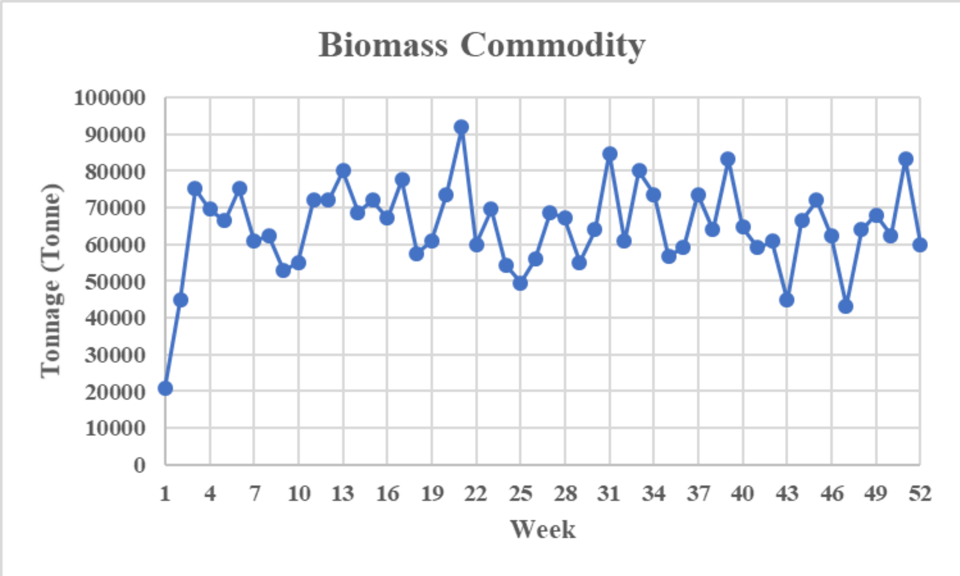


Figure 65 Biomass commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (weekly basis)

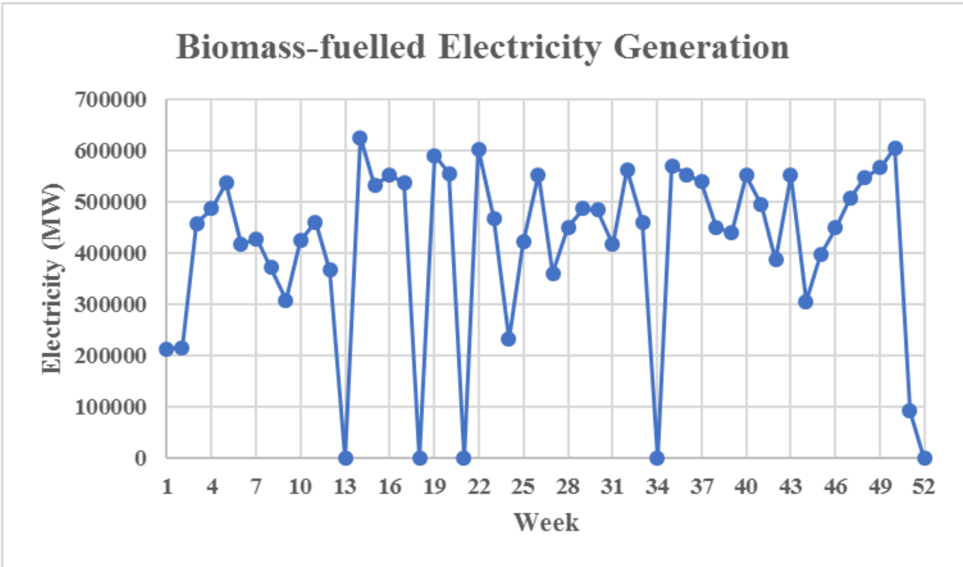


Figure 66 Biomass-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (weekly basis)

For biomass, the electricity generation is seasonal, as shown by a curve going through a sinusoidal-like wave indicating a repeated behaviour. However, power generation reliant on coal has not shown a seasonal or repeating pattern.

It should be noted that the traffic demand (for coal/biomass transport) from power stations frequently changes due to various factors, and freight train operation patterns also change accordingly. For example, in January or March demand may be different to the average because of the New Year or the end of the financial year.

In terms of dependency, as previously mentioned, stakeholders/subject matter experts stated that biomass cannot be technically stored for longer than approximately a week in the power plant. This further explains the close correlation between commodity supply and electricity generation graphs. It also indicates that electricity generation based on biomass is tightly dependant on a more frequent commodity supply than that the supply of coal.

Furthermore, stakeholders stated that power plants buy coal when the price in the market is lower and stockpile the commodity. Unlike biomass, coal can technically be stockpiled in the premises of the power plants and be used when required (as demanded by National Grid). Assuming the above-mentioned statement is true, it can be concluded that for biomass, train movements need to be frequent and hence power generation depends on it. However, for coal, as there is usually stock available, the train movement depends on the price of coal on the market.

Stakeholders discussed that the power plants generate coal-fuelled electricity only when demanded by the National Grid if a shortage is observed, while biomass-fuelled electricity generation is frequent and hence shows a repeating pattern. Overall it is observed that the supply chain of biomass for ESI appeared to be demand-related whereas for coal it would be price-oriented.

To investigate the same data at a daily level and to potentially assess the capability/flexibility of the power station in absorbing shocks during disruptions, the following analyses are carried out. As Figure 67, Figure 68, Figure 69, Figure 70, Figure 71, Figure 72 and Figure 73 show, on certain days the quantity of commodity or power generation is zero. In total, the number of days with no coal commodity moved by trains to the power station is higher than the number of days without biomass commodity moved to Drax. Similarly, the number of days without coal-fuelled power generated was higher than the number of days when no biomass-fuelled power was generated. This trend is even more obvious for 2018 when Drax started reducing coal-fuelled power production significantly. This observation confirms the stakeholders' statement regarding a growing tendency of Drax (and in general UK power stations) to diminish reliance on coal for producing energy. Furthermore, considering that the data related to biomass commodity and its relevant production is more tightly dependent, a specific pattern could be observed in both years. For instance, as Figure 70 shows Drax generated no electricity from day 65 to day 81 in 2017. Correspondingly, no biomass commodity was moved to Drax from day 73 to 89 in 2017. This data show that the power station stopped biomass-fuelled electricity generation (on day 65) but continued receiving biomass supply for several days (up to day 73) until the commodity movement dropped to zero. Furthermore, the power stations started generating electricity out of the available biomass stored in stock (after day 81) and about a week later movement of biomass to the power station started (after day 89). Therefore for 17 days of no biomass-fuelled electricity generation, the relevant commodity movement stopped for 17 days. This certainly indicates a planned closure of Drax within that period. It also indicates clear proactive behaviour in a planned closure scenario (e.g. the power plant consumes the commodity that was brought to the power station after the closure and well before the reopening). Observing such behaviour, it can be argued that the biomass-fuelled power production depends on the supply of the commodity within a 7 to 10-day period before the time of electricity generation. Similar planned closure patterns could be observed for other periods in 2017 (e.g. day 233-239 and day 252-258), while such closures were shorter in duration. For 2018, since in total biomass-fuelled electricity generation increased and closure periods were not as long, the supply of biomass commodity appeared more frequent showing a smaller number of zero days. Hence, it is difficult to observe any pattern related to zero values in the available data. The short periods of zero biomass-fuelled electricity generation could be either planned or unexpected and due to various reasons (e.g. demand, market price, incidents etc). As for the coal data, there is a significant reduction in commodity movement in 2018 compared to 2017 and a drop in coal-fuelled electricity generation. It is impossible to interpret the pattern of data related to coal, since Drax planned to decrease its dependency on coal and generated coal-fuelled electricity mostly in colder seasons where energy demand could be supposedly higher. The available dataset indicates a very small quantity of coal commodity moved in this year but whether Drax actually produced all power using commodity available in stock or whether some movement data is missing is unknown.

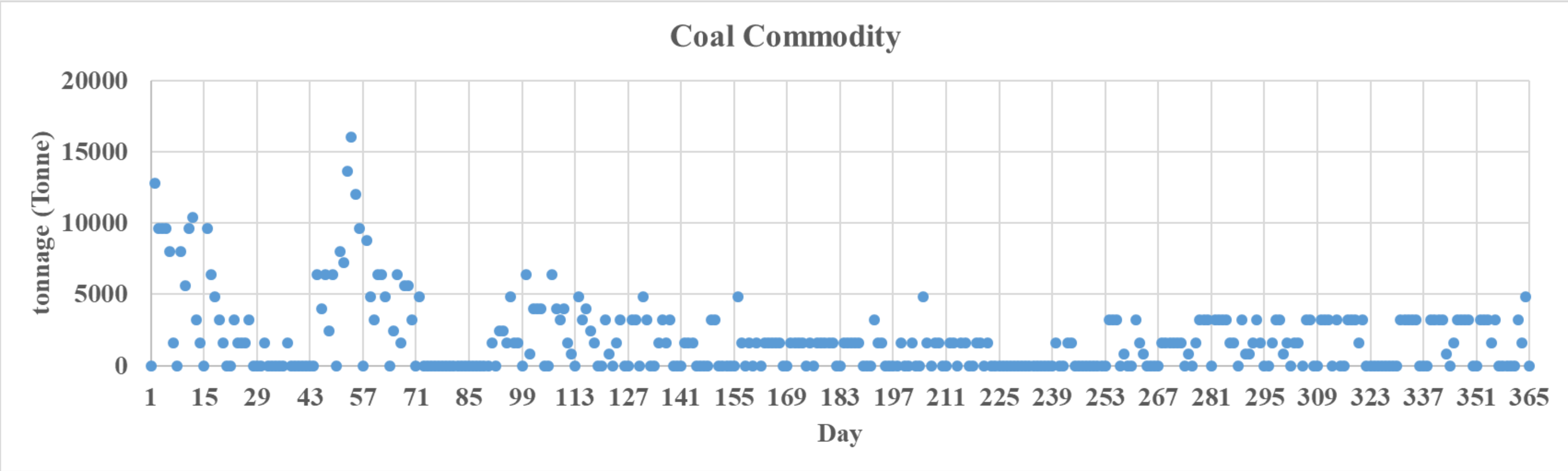


Figure 67 Coal commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (daily basis)

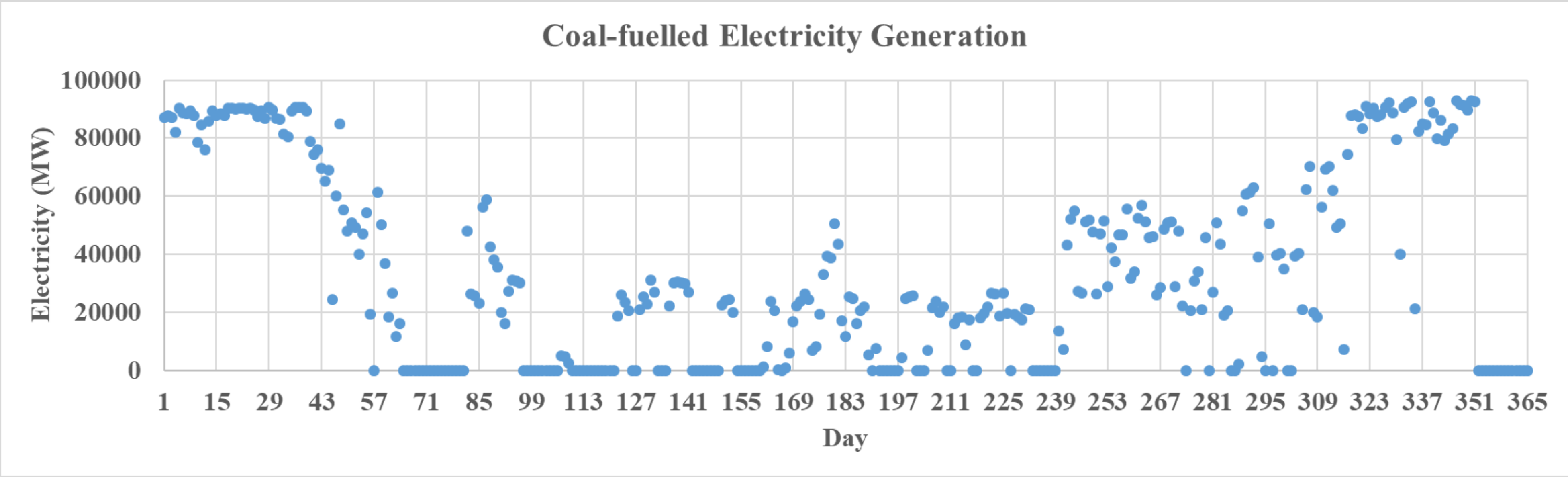


Figure 68 Coal-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (daily basis)

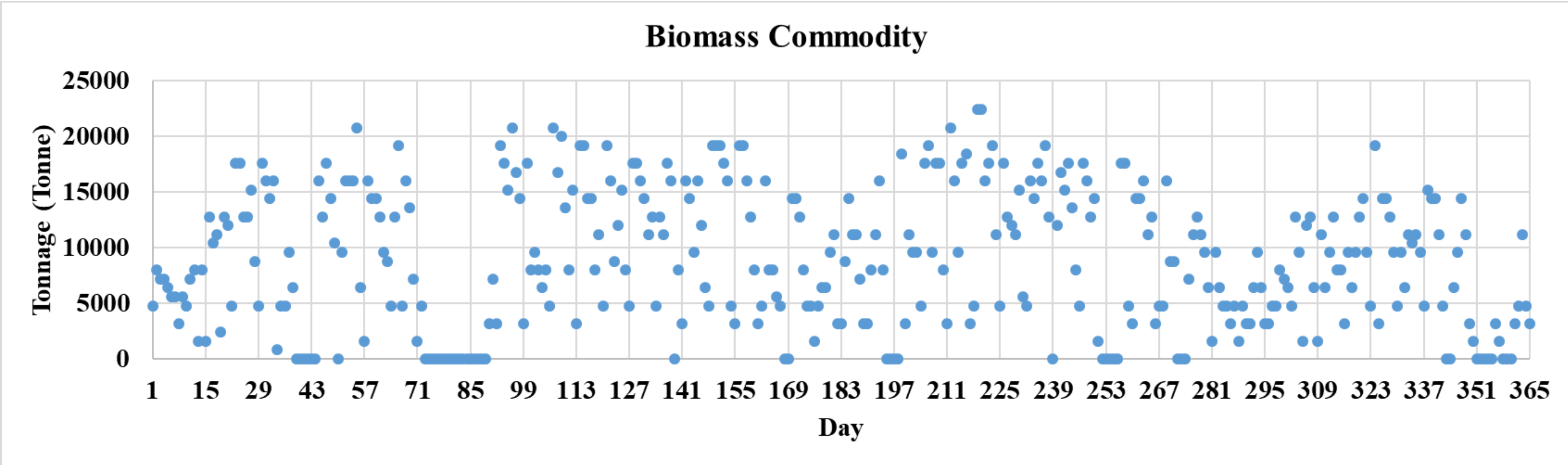


Figure 69 Biomass commodity transported by railway to Drax between 01/01/2017 and 17/12/2017 (daily basis)

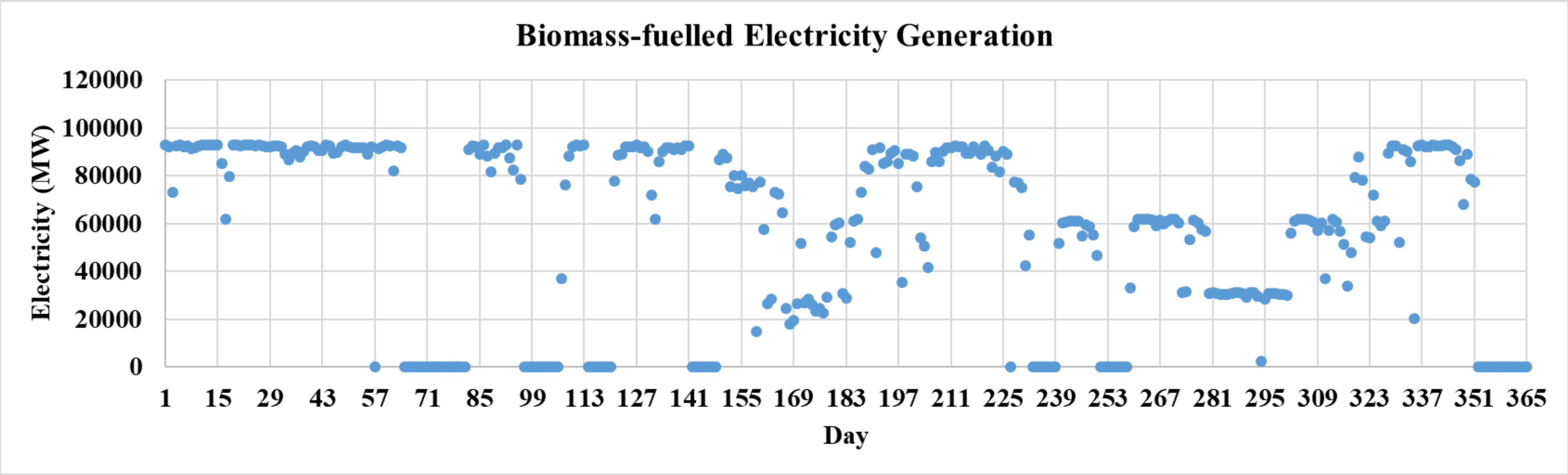


Figure 70 Biomass-fuelled power generation at Drax between 01/01/2017 and 17/12/2017 (daily basis)

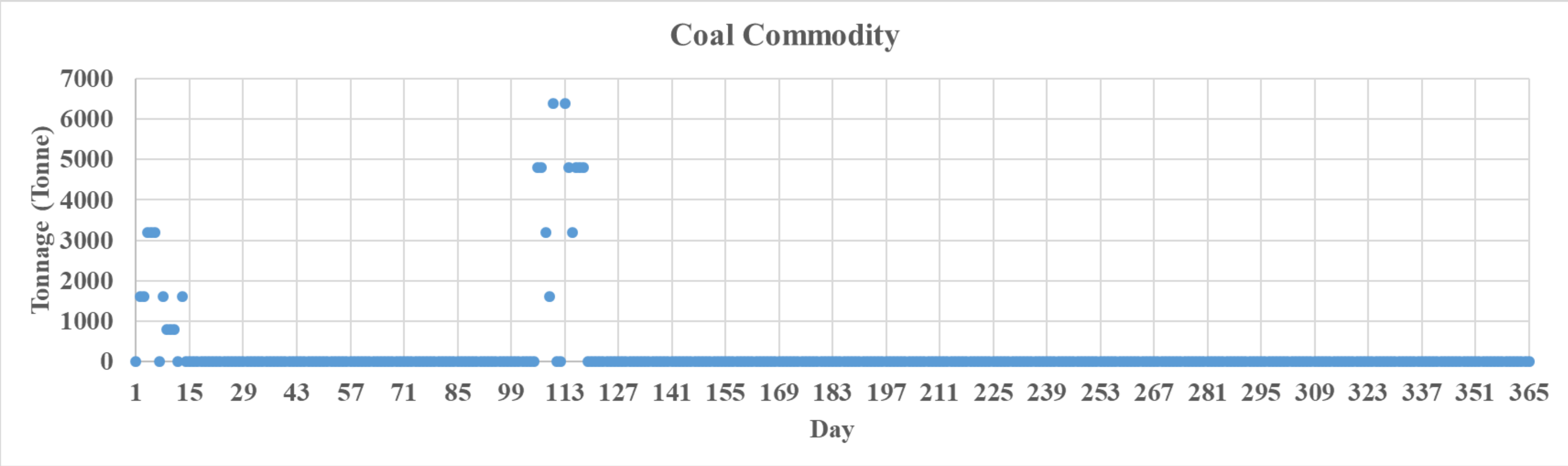


Figure 71 Coal commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (daily basis)

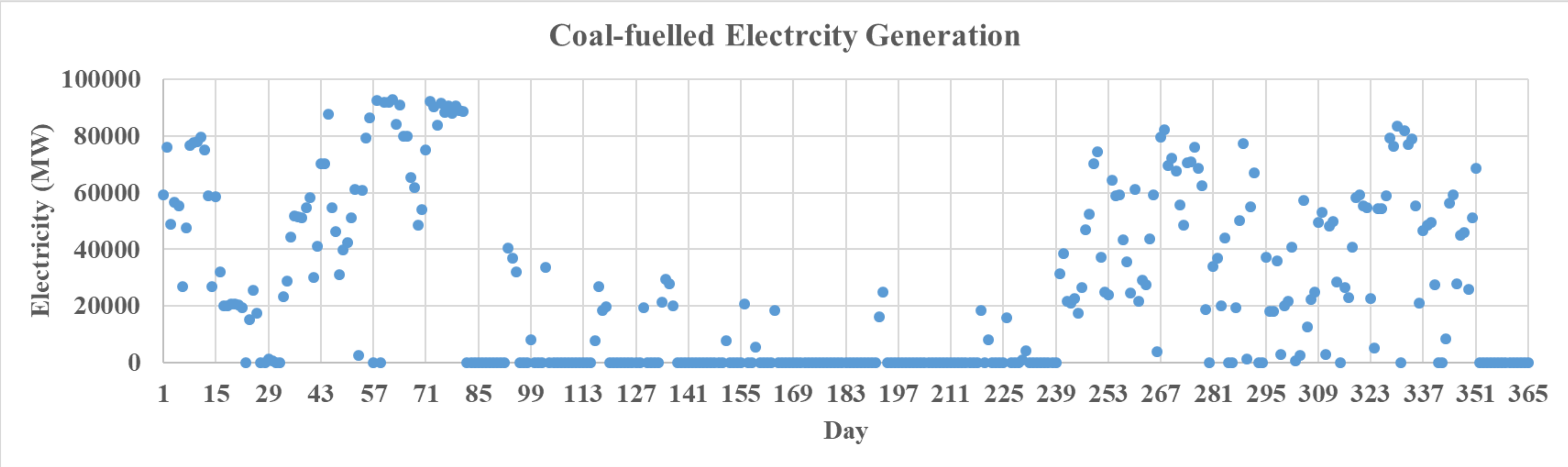


Figure 72 Coal-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (daily basis)

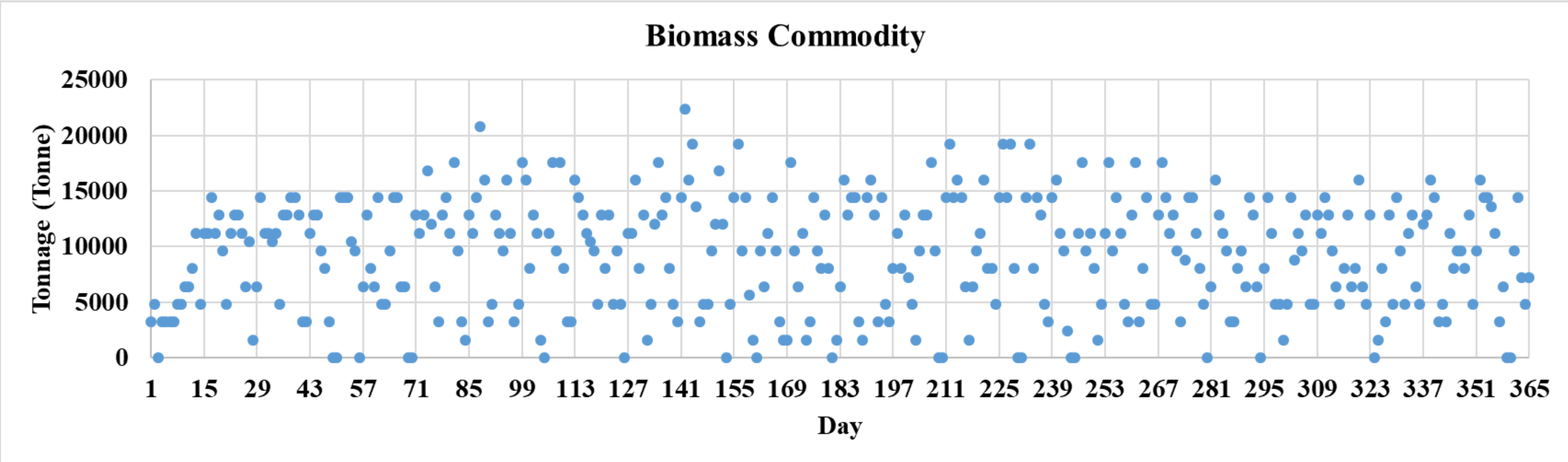


Figure 73 Biomass commodity transported by railway to Drax between 01/01/2018 and 17/12/2018 (daily basis)

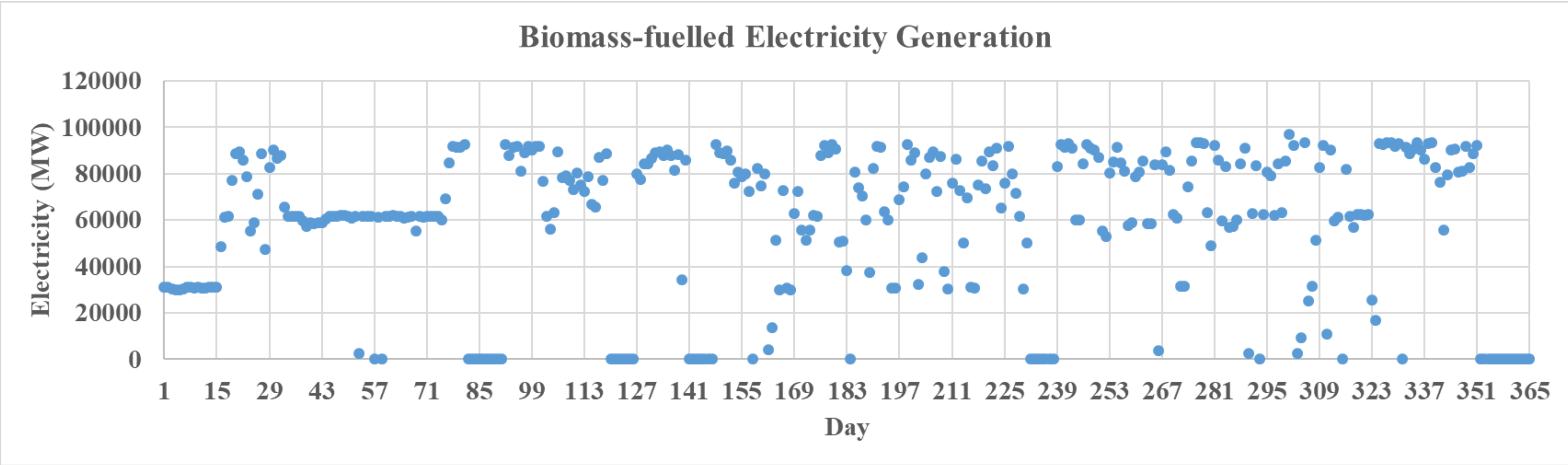


Figure 74 Biomass-fuelled power generation at Drax between 01/01/2018 and 17/12/2018 (daily basis)

Next, the train movement data is analysed to investigate whether any patterns can be observed in the arrival times of the commodity at Drax regarding days of the week. The variability of traffic and electricity production during a week can potentially indicate the capability/flexibility of the infrastructure systems for absorbing shocks (i.e. during disruptions). Table 20 shows that in 2017, most of the biomass commodity arrived at Drax on Mondays followed by Tuesdays and Thursdays. On Wednesdays and Fridays, the quantity of the arrived commodity reduced and finally weekends were the least popular days to receive biomass commodity at Drax. Regarding the average value and standard deviation, the average value on Sundays is relatively smaller, while the values of standard deviation for the weekdays usually increase as the value of the average increases. Hence, it suggests that the commodity supply on any weekday does not necessarily show more vulnerability to shocks compared to the other days of the week (during disruptions). However, since weekends are generally less popular for commodity movement, shocks (e.g. engineering works) are considered as more absorbable for the dynamics of the supply during these times.

As for 2018, Table 21 shows that Tuesdays and Thursdays were the busiest days of the week for Drax power station to receive biomass commodity. While the total biomass quantity (or number of biomass trains) moved to Drax reduced on Wednesdays, Mondays and Fridays and this quantity reduced much further during weekends. Hence, for both years, commodity supply was limited during weekends especially on Sundays when the total quantity of commodity equalled only about 23% of the total from the most popular day of the week and about 60% of the total commodity moved on second least popular day of the week. If this pattern persists, it can be argued that Mondays to Thursdays stay the busiest weekdays for train traffic at and near the power station area, which can potentially increase its vulnerability to supply failure, especially if the demand for supply increases in the future. Regarding the standard deviation, the values usually increase as the average values increase and hence, no particular vulnerability to shocks are observed solely due to the probability distribution on specific weekdays. Note that for both years the distribution of biomass movement in terms of both sum and average commodity tonnage showed the same trend and hence the trend of supply was quite consistent.

As for coal commodity movement, data for 2017 (Table 22) show that similarly, Mondays to Fridays were more popular for trains to move commodity to Drax power station while Saturdays were less popular for train movement and no coal carrying trains arrived at Drax on Sundays. Regarding the standard deviation, no particular vulnerability to shocks are observed solely due to the probability distribution on specific weekdays. Once more, for coal, the distribution of commodity movement (in terms of both sum and average commodity tonnage) showed the same trend and hence the trend of supply was quite consistent. It is difficult to interpret such data for 2018, since coal supply was very limited (or part of the data was not captured by the available dataset).

Regardless of the commodity type, Mondays were the busiest day in terms of traffic at and near the power station area in 2017, while Tuesdays were the busiest day in the same term in 2018. To summarise, the data shows that the beginning of the working week could be considered as a critical time for the relevant railway network to operate to meet the requirement of its customers (freight operating companies).

Table 20 Distribution of arrival times (days of a week) for biomass commodity supply at Drax in 2017 based on the total and average amount moved

Weekday	Sum of biomass commodity tonnage (Tonne)	Average of biomass commodity tonnage (Tonne)	Standard deviation (Tonne)
Monday	599200	11523	6760
Tuesday	589600	11338	6356
Wednesday	526400	10123	5705
Thursday	576800	11092	5426
Friday	483200	9292	6058
Saturday	324000	6231	4031
Sunday	153600	2898	1928

Table 21 Distribution of arrival times (days of a week) for biomass commodity supply at Drax in 2018 based on the total and average amount moved

Weekday	Sum of biomass commodity tonnage (Tonne)	Average of biomass commodity tonnage (Tonne)	Standard deviation (Tonne)
Monday	558400	10536	3792
Tuesday	676000	13000	4691
Wednesday	560800	10785	3924
Thursday	625600	12031	4242
Friday	528000	10154	3451
Saturday	259200	4985	3520
Sunday	153600	2954	1885

Table 22 Distribution of arrival times (days of a week) for coal commodity supply at Drax in 2017 based on the total and average amount moved

Weekday	Sum of coal commodity tonnage (Tonne)	Average of coal commodity tonnage (Tonne)	Standard deviation (Tonne)
Monday	144000	2769	2818
Tuesday	122400	2354	2128
Wednesday	105600	2031	2695
Thursday	132000	2538	3009
Friday	104000	2000	2277
Saturday	49600	954	1875
Sunday	0	0	0

The data related to electricity generation is also analysed regarding weekday distribution. As Table 23 and Table 24 show, there is almost no significant difference between the total amount of biomass-fuelled electricity generation on different days of the week. A similar trend is observed for the average values of biomass-fuelled electricity generation and their standard deviations on different days of the week. Table 25 and Table 26 show that the total amount of coal-fuelled electricity generation decreased during weekends. The descending order is the same for both sum and average values with a slight difference between the values of coal-fuelled electricity generation on Saturday and Sunday in 2017 (Table 25). Regarding the standard deviation, no particular vulnerability to shocks are observed solely because of the probability distribution on specific weekdays.

In general, regardless of the type of fuel, the amount of electricity generation appears to be consistent in a week. However, the train movement and hence the total amount of commodity supply clearly varies in a week. This coincides with the fact that a power station generates electricity as demanded by National Grid, while railway traffic depends on factors such as staff and network availability. Also, while the final product of a freight rail service (e.g. coal or biomass) can be stored in the stock, the electricity as the main output of power stations cannot be stored and must be provided continuously.

Table 23 Distribution of sum and average of biomass-fuelled electricity generation during days of a week in 2017

Weekday	Sum of biomass-fuelled electricity generation (MW)	Average of biomass-fuelled electricity generation (MW)	Standard deviation (MW)
Monday	2824615	54320	34739
Tuesday	3004351	57776	35535
Wednesday	3167324	60910	34901
Thursday	3156123	60695	34176
Friday	3013924	57960	36449
Saturday	2918844	56132	36986
Sunday	2980524	56236	36496

Table 24 Distribution of sum and average of biomass-fuelled electricity generation during days of a week in 2018

Weekday	Sum of biomass-fuelled electricity generation (MW)	Average of biomass-fuelled electricity generation (MW)	Standard deviation (MW)
Monday	3380665	63786	30805
Tuesday	3246603	62435	34353
Wednesday	3195682	61455	32961
Thursday	3221168	61946	31124
Friday	3196624	61474	29095
Saturday	2684293	51621	29249
Sunday	2677208	51485	30036

Table 25 Distribution of sum and average of coal-fuelled electricity generation during days of a week in 2017

Weekday	Sum of coal-fuelled electricity generation (MW)	Average of coal-fuelled electricity generation (MW)	Standard deviation (MW)
Monday	1849354	35565	32210
Tuesday	1964325	37775	33081
Wednesday	1925536	37030	31964
Thursday	1959152	37676	31316
Friday	1854167	35657	32263
Saturday	1427028	27443	34060
Sunday	1438017	27132	34342

Table 26 Distribution of sum and average of coal-fuelled electricity generation during days of a week in 2018

Weekday	Sum of coal-fuelled electricity generation (MW)	Average of coal-fuelled electricity generation (MW)	Standard deviation (MW)
Monday	1441782	27203	30886
Tuesday	1479822	28458	32141
Wednesday	1364600	26242	30501
Thursday	1545260	29717	30332
Friday	1356970	26096	30388
Saturday	1041258	20024	26870
Sunday	956526	18395	25998

Moreover, investigating patterns of the two-year dataset could highlight information regarding the variability in usual operation and hence could potentially support decisions regarding disruptions and shocks. Therefore, it is also beneficial to consider the total daily amount of electricity produced in Drax power station in a two-year period and compare such figures with the total daily amount of electricity generated in the UK in the same period. As Figure 75 and Figure 76 show, Drax produced between 0.04 to 0.1 of the UK electricity daily in 2017 and 2018 (except when the power plant was closed). As for the National Grid, the maximum amount of generated electricity in one day was 1.9E+06 MW (on 23/01/2017) while the maximum amount of electricity produced by Drax in one day was 1.8E+05 MW (on 07/02/2018). Studying both figures shows that usually during the colder seasons in the UK (e.g. between September and March) the amount of electricity produced increases, while relatively smaller amounts of electricity is generated in warmer seasons. Generally, Drax follows a similar pattern to the National Grid in terms of power production which indicates the dependency of the whole UK Grid on individual power stations. Note that some of the data related to electricity generation such as those related to the end of 2017 might have not been captured in the source of this dataset and might be missing.

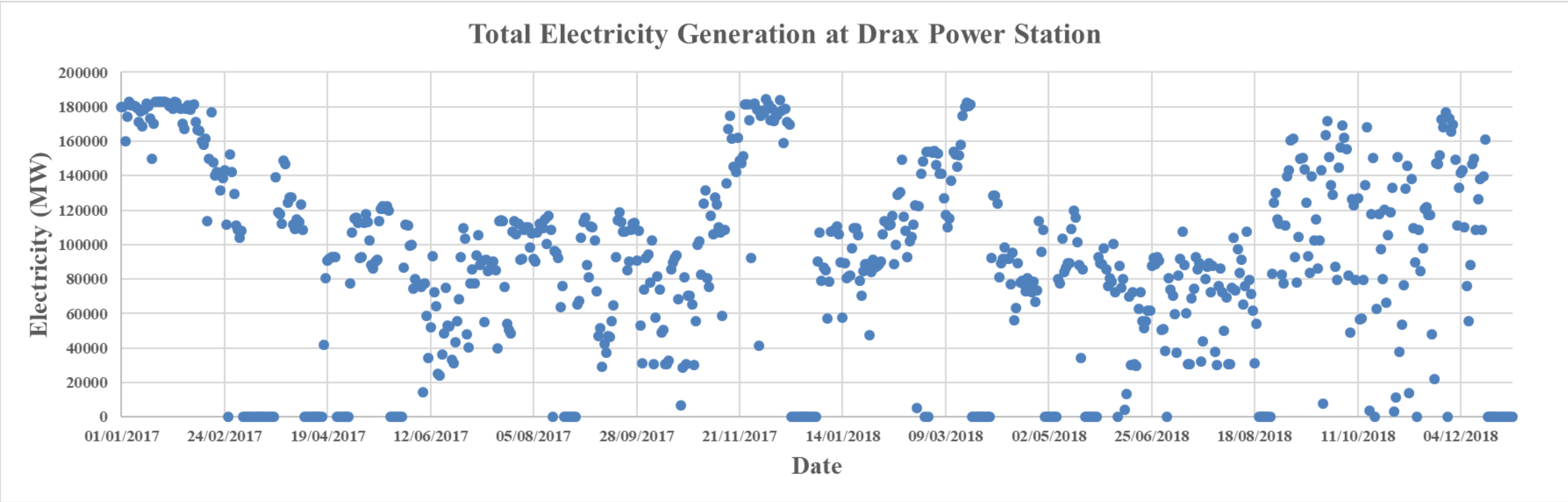


Figure 75 Total amount (MW) of electrcity generated daily at Drax power station in 2017 and 2018

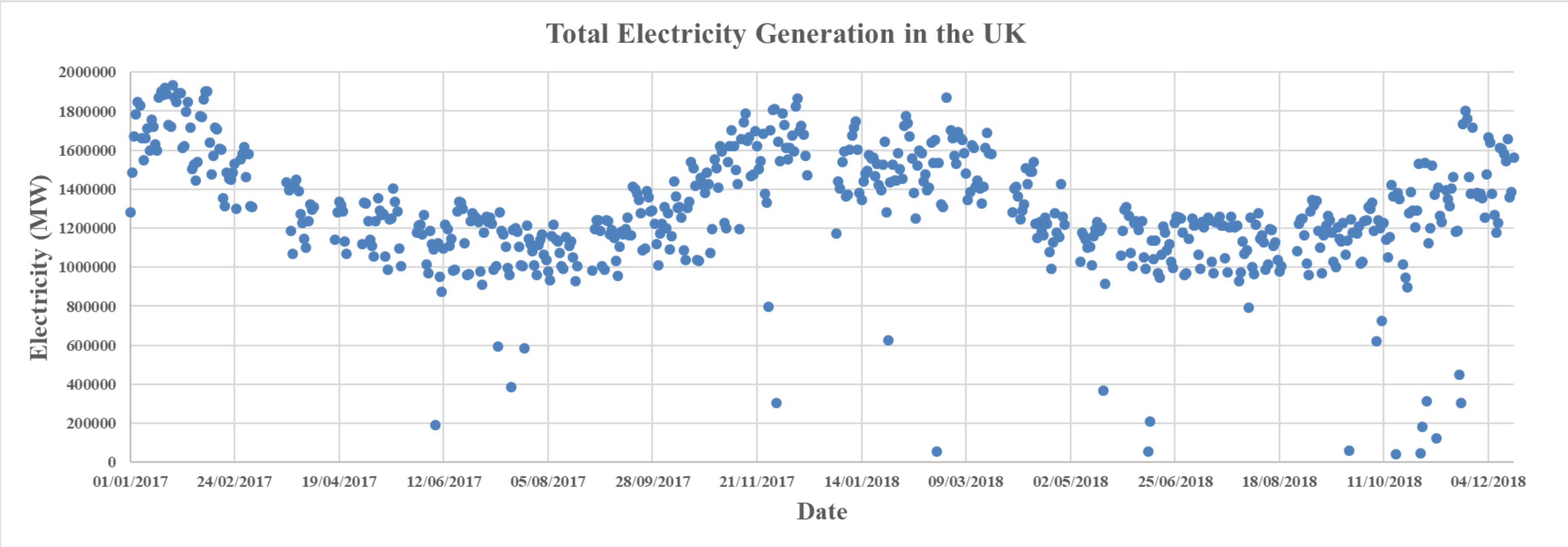


Figure 76 Total amount (MW) of electrcity generated daily in the UK power stations in 2017 and 2018

4.7.4 Descriptive statistics

Whereas in the previous section, the results of commodity movement and electricity generation were analysed in terms of the overall pattern, this section focuses on the measures of central tendency and measures of variability/dispersion in the datasets instead. The analysis of central tendency and variability of commodity movement and elecrcity generation can potentially provide useful insights regarding the regularity of the data and hence the capability to absorb shocks. The analysis known as descriptive statistics summarises a given dataset using brief descriptive coefficients such as mean/average, median, mode, skewness and confidence level.

As for the daily level, the descriptive statistics (shown in Table 27) show that on average 1802 tonnes of coal were moved by train to Drax per day in 2017. Note that since each full train is assumed to carry 1600 tonnes of commodity, the average value indicates that on average, approximately one coal train a day moved to Drax in 2017. This average value decreased to nearly zero trains a day in 2018. However, as previously mentioned some data might have been lost and so the 2018 figures for coal may not be fully representative. For the biomass commodity, an average of between 5 to 6 trains per day moved to the power station in 2017 and 2018 with a standard deviation of almost 4 trains and 3 trains in 2017 and 2018 respectively. These figures indicate the popularity of biomass as an energy source in Drax (compared to coal). Also, the standard variation shows that the commodity movement is relatively variable in order to meet the demand. The median, which is the middle value in the sorted dataset and dividing the dataset into two different groups of the same size (say in the ascending/descending order of the daily amount of commodity moved for each year), appeared to be moderately different to the mean/average for all datasets. However, yet for all datasets both mean, and median values can be considered as representatives of the central tendency of one dataset (e.g. biomass commodity in 2018). Note, although for moved commodity/trains to Drax mean and median values are not massively different, generally the lower value between the mean and median could be considered as more representative (say 1 coal-carrying train in 2017 and 5 biomass-carrying trains in both 2017 and 2018 arrived in Drax). Moreover, the values of the mode appear very different to the values of the mean and median within one dataset. The most frequent values for all datasets except for biomass commodity in 2018 was 0 (i.e. no train per day). As this trend changed in 2018 for biomass commodity movement, it can be argued that commodity arrival became more frequent and it was common to have 9 biomass-carrying trains arriving at Drax power station daily. This indicates a significant behavioural change in demand of moved biomass commodity to the power station (and hence the rail traffic).

Considering the skewness and the distribution of the data, none of the datasets (i.e. represented by each column) expressed a symmetrical distribution (where the skewness is zero and mean, median and mode are all equal). In a positive skewness the mean value is greater than the median and the median is greater than the mode. This explains that the most frequent value (i.e. quantity of commodity moved) is located within the first half of the dataset (sorted in ascending order) while the average is located within the second half and hence the sorted data is skewed to the right (larger values). A positive skewness is observed in the data related to quantity of coal commodity in both years and biomass commodity in 2017. The data of quantity for biomass commodity in 2018 is less asymmetrical (skewness near zero) which means the daily values occur at relatively more regular frequencies. Quantities of biomass commodity show a negative skewness of relatively small values (near zero).

Hence in terms of the frequency, it is conclusive that the commodity movement is not generally symmetrical (i.e. frequency of the quantities is not perfectly regular). Yet again this indicates that freight movement is quite dynamic (i.e. diverse and variable) in nature. However, for biomass-related datasets the near zero skewness values indicate that the biomass movement is less irregular than the coal movement. The negative skewness for quantity of biomass commodity in 2018 shows the mean is slightly smaller than the median which is smaller than the mode and the mass of the distribution is concentrated in the larger values.

Table 27 Descriptive statistics of daily commodity supply to Drax

Descriptor	Coal commodity in 2017	Coal commodity in 2018	Biomass commodity in 2017	Biomass commodity in 2018
Mean (Tonne)	1802	186	8912	9210
Median (Tonne)	1600	0	8000	9600
Mode (Tonne)	0	0	0	14400
Standard deviation (Tonne)	2469	867	6140	5077
Skewness	2.2	5.2	0.1	-0.9

As for the daily electricity generation at Drax, Table 28 shows that on most days no electricity was generated at all while the values of the mode appear quite different to the values of the mean and median within each dataset. The average of daily coal-fuelled electricity generation decreased in 2018 compared to the previous year, while the average daily biomass-fuelled electricity generation increased in 2018. On average, Drax generated more biomass-fuelled electricity daily than coal-fuelled electricity while the median values for coal-fuelled electricity generation and mean values for biomass-fuelled electricity generation could be taken as the measure of central tendency. A standard deviation of between 30,000 MW to 35,000 MW is observed for all datasets that measure the dispersion of values differing from mean values. Furthermore, although the distribution of the data is not symmetrical the value of skewness in all datasets is near zero which shows the pattern of electricity generation is fairly regular.

Table 28 Descriptive statistics of daily electricity generation at Drax

Descriptor	Coal-fuelled electricity in 2017	Coal-fuelled electricity in 2018	Biomass-fuelled electricity in 2017	Biomass-fuelled electricity in 2018
Mean (MW)	34021	25168	57714	59184
Median (MW)	24688	15236	61904	62621
Mode (MW)	0	0	0	0
Standard deviation (MW)	32771	29676	35476	31406
Skewness	0.6	0.8	-0.6	-0.8

Focusing on the biomass commodity flow between the railway and the power station as outlined by the framework for the analysis (in section 4.5), the inflow of biomass (i.e. the biomass commodity moved by rail to the power station) and the outflow (i.e. the biomass-fuelled electricity generated) can be compared. For the purpose of a comparison between the standard deviation values, the following assumptions are considered:

- In order to consider the weekly inflow and the weekly outflow of the two-year data in the same unit (say in Tonne as shown in Table 29) a conversion factor (say α) should be used.

- For the calculation of a conversion factor, first the sum of the weekly inflow (in tonnes) for the whole two years as well the sum of the outflow (in Megawatt) for the whole two years are considered.
- The stock level of day zero (before the first day of the two years) and the stock of the last day of the two years are ignored.
- Assuming that all inflow is used to generate outflow (i.e. no loss) and therefore, calculating the conversation factor as $\alpha = \frac{\text{sum of the weekly outflow}}{\text{Sum of the weekly inflow}}$, on average about 6.45 MW of biomass-fuelled electricity is generated out of 1 tonne of biomass. An accurate conversion factor of $\alpha = 6.452326782$ can be obtained and used for calculating the values of standard deviation as shown in Table 29.

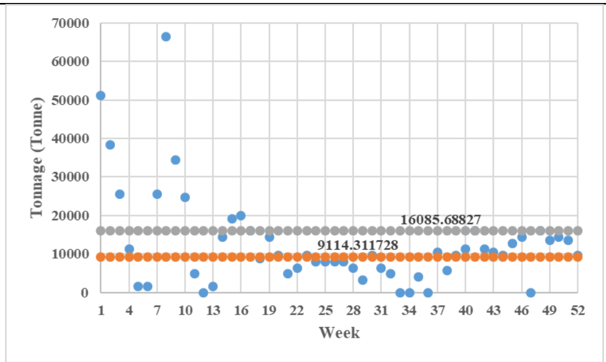
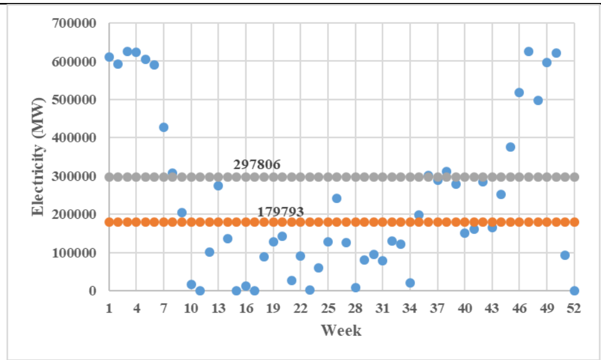
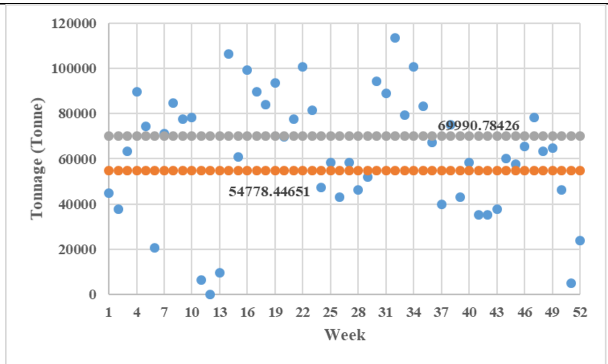
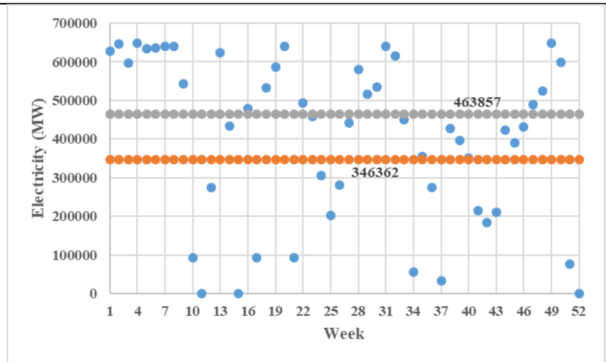
The results (Table 29) show that over the two years, on a weekly basis, the inflow varied by 33% while the outflow varied by 47%. The high level of variety shows that the railway should be capable of accommodating about 14 trains a week in addition to the average number of trains (say 40 trains a week) in order to meet the demand of the power station. The percentage values (33% and 47%) indicate a relatively high variation from week to week for both inflow and outflow from the start of 2017 to the end of 2018, which could represent the seasonality characteristics in the data. Such characteristics can be explained by phenomena such as the boosted inflow and outflow from time to time due to a rise in demand in specific times (e.g. during cold seasons when National Grid demands power stations to generate a higher amount of electricity compared to their usual i.e. average/mean amount of production).

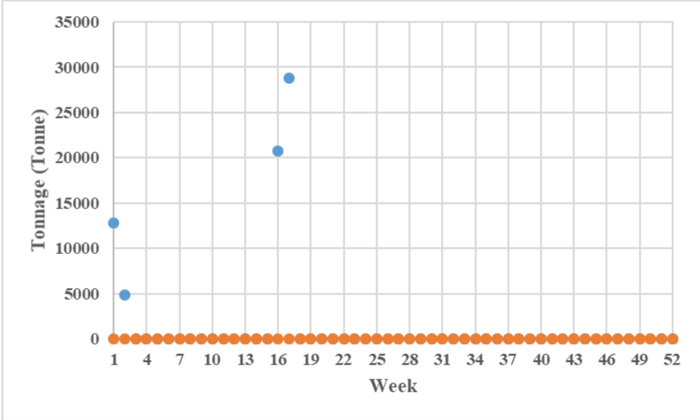
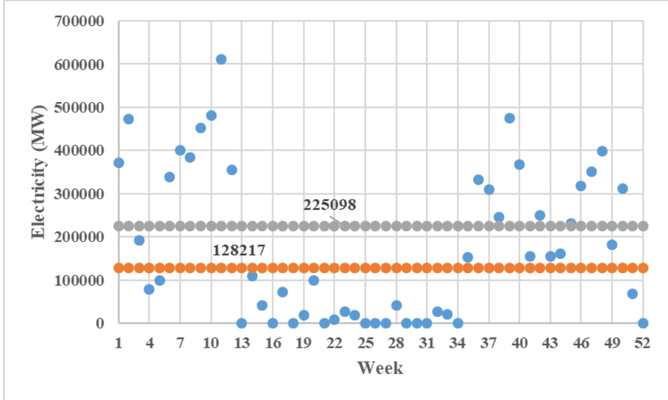
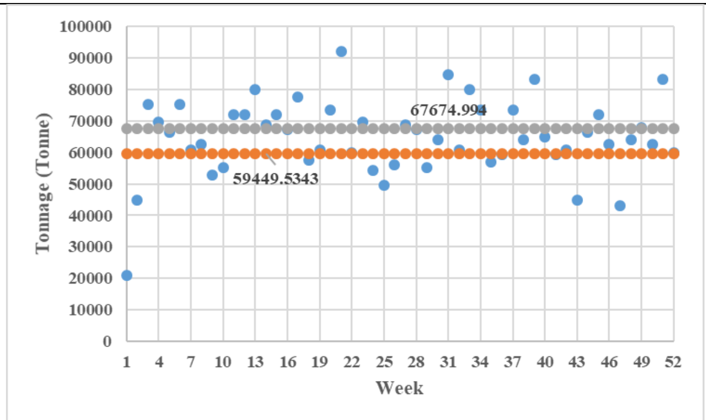
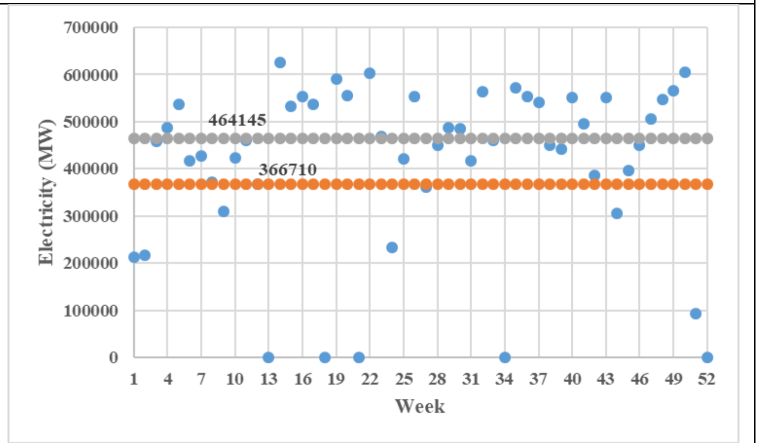
Table 29 Comparison of variation of inflow of biomass and outflow of biomass-fuelled electricity for the two-year data (weekly basis)

	Two-year data (2017 and 2018)	
	Inflow (Tonne)	Outflow (Tonne)
Mean	63584.62	63584.62
Standard deviation	21058.58	29906.94
Percentage of standard deviation to mean value	33%	47%

As for the 95% confidence level of the commodity supply/movement as well as power generation on a weekly basis, the data can be presented and compared pairwise in Table 30. This shows that with a relatively high confidence on average, between 6 to 10 coal trains arrived in Drax in 2017. While most weeks an amount of between 1.8e+05 to 3e+05 MW of coal-fuelled electricity was generated per week. For biomass, between 34 to 44 biomass trains in 2017 and between 37-42 biomass trains in 2018 arrived in Drax most weeks. It's most likely that the amount of biomass-fuelled electricity generation lies between 3.5e+05 to 4.6e+05 in 2017 and between 3.7e+05 to 4.6e+5 in 2018. Whether these figures are representative of how much commodity converts into a MW of electricity or not needs further investigation and cannot be argued solely based on the above values (since a consideration of the stock level for storable commodity in the power station is needed). However, this analysis shows that as for biomass, the amount of moved commodity and generated electricity during a week in both years are similar. Hence, in case of a disruption in commodity supply for a duration of more than a week (when it is assumed that the biomass supply runs out) potentially a shortage of more than 3.5e+05 MW in electricity generation might occur.

Table 30 Commodity supply and power generation for Drax in 2017 and 2018 with 95% confidence level statistics

		Commodity Supply	Power Generation
2017	Coal		
	Biomass		

2018	Coal		
	Biomass		

4.7.5 Correlation

The previous section shows the trend between coal and biomass supply and electricity production. However, it is not very clear whether there is a dependency between them or not. To investigate whether there is any dependency between the supply and the production, the autocorrelation function is used here. Autocorrelation indicates whether there is any pattern in the data (the data repeats itself in a systematic way) or the data forgets itself after a specific time (random). If the autocorrelation of the supply is similar in behaviour to that of the electricity production, then there is an indication that there is a strong dependency between them. However, if the behaviours of the two autocorrelations are different then there is no dependency between the supply and the production.

The correlation of electricity generation and commodity supply depends on the type of fuel. Figure 77 and Figure 78 show the weekly autocorrelation of both biomass supply and electricity production for years 2017 and 2018, respectively. It is clear that the behaviours of the correlation curves for both electricity generation and commodity supply are similar in the two years. In addition, the biomass curves for the autocorrelation show apparent periodicity, meaning that the data is not random. It can also be seen that both autocorrelations of commodity and production behave the same way, i.e. have the same correlation or periodic behaviour. This shows the strong dependency of the two sets of data.

Figure 79 and Figure 80 show the weekly autocorrelation curves for both the coal commodity and electricity production for years 2017 and 2018, respectively. Both curves show autocorrelations that go to zero quickly meaning that they do not have a specific pattern in time (i.e. both are random) and no strong dependency is observed between them.

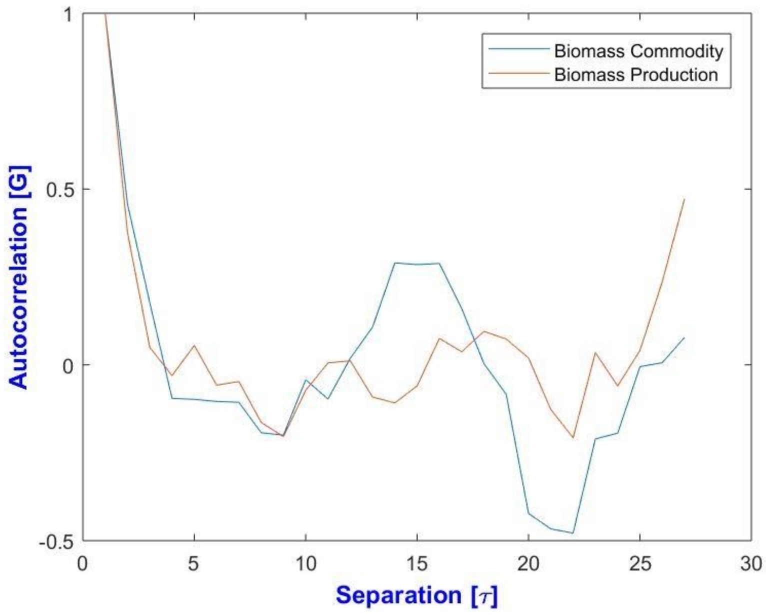


Figure 77 Autocorrelation for biomass commodity and biomass-fuelled power production for 2017- weekly basis

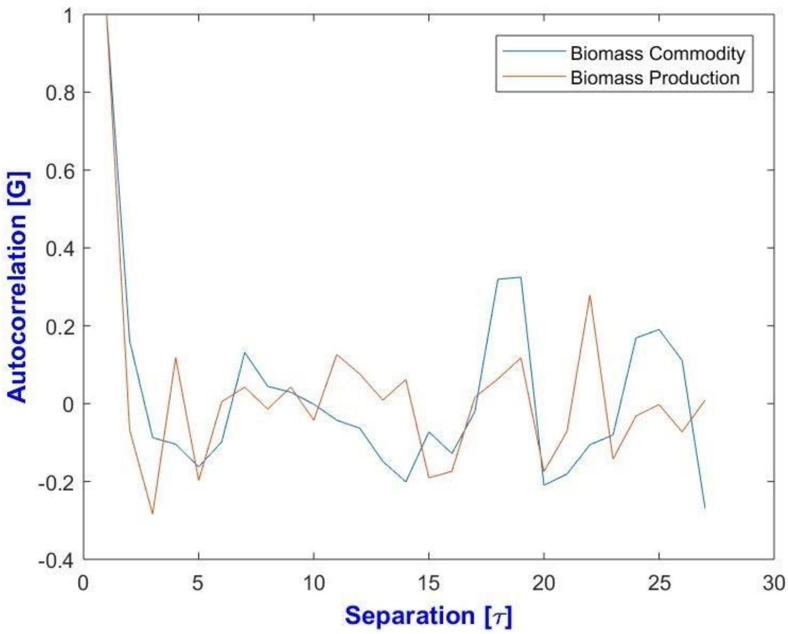


Figure 78 Autocorrelation for biomass commodity and biomass-fuelled power production for 2018 - weekly basis

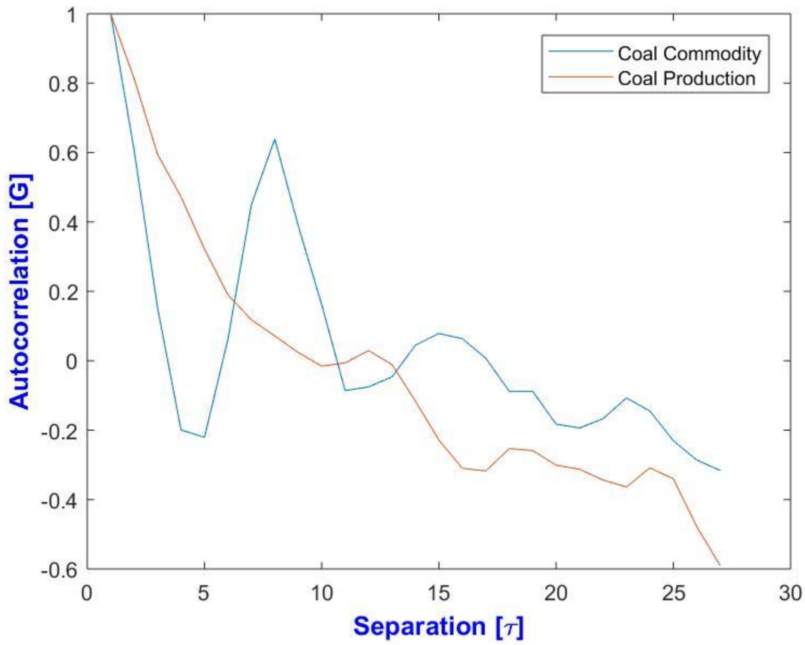


Figure 79 Autocorrelation for coal commodity and coal-fuelled power production for 2017- weekly basis

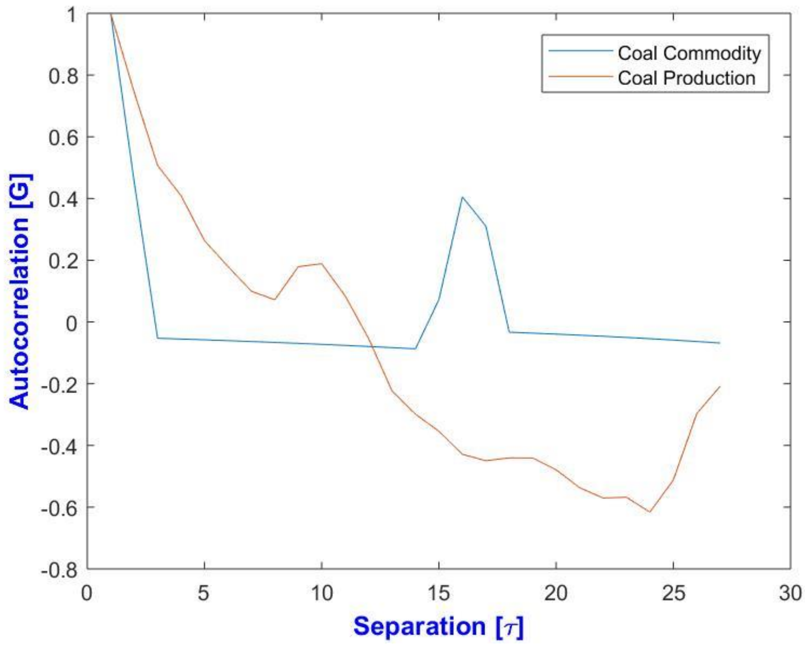


Figure 80 Autocorrelation for coal commodity and coal-fuelled power production for 2018 – weekly basis

In addition to the time series analysis shown in Figure 77, Figure 78, Figure 79 and Figure 80 the correlation between the freight volume and power generation is further studied using the Pearson correlation coefficient (refer to Mendonca et al., 2004 for a similar investigation). Here the value of r or the coefficient value for the supply of coal and power production is 0.1 while that for the biomass and the power production is 0.35. This supports the previous analysis and indicates a strong dependency between the biomass supply and the power production while the small value of r for the coal supply and the power production indicates a smaller dependency between them.

4.7.6 ARIMA modelling

For further assessment of the dependency between commodity movement and electricity generation, this section uses ARIMA modelling as a method for further time series analysis. This analysis is carried out for the commodity and electricity generation data which was collected over two years (2017 and 2018) and investigated in the previous section. Data gathered sequentially in time is called a time series and one of the objectives of a time series analysis is to describe and interpret the time dependence in the data and whether it is possible to forecast future values. A useful model for analysing patterns in a time series data is ARIMA modelling. According to Tabachnick et al. (2007), ARIMA (that stands for Auto-Regressive Integrated Moving Average) explicitly includes the following components as parameters:

- autoregression is a model that uses the dependent relationship between an observation (e.g. commodity quantity) and some number of lagged observations,
- integrated is the use of differencing raw observations in order to make the time series stationary (so statistical properties such as mean, variance, autocorrelation, etc. are all constant over time)
- and moving average which is a model that uses the dependency between an observation and a residual error from a moving average model and applies it to lagged observations (Tabachnick et al., 2007).

Therefore, The ARIMA model of a time series is defined by three terms (p, d, q) where d is the trend component (to make the process stationary) and p and q are respectively autoregression and moving average components.

The identification step of a time series is the process of finding integer values of p, d, and q that model the patterns in the data, which are usually very small (e.g., 0, 1, or 2). When the value is 0, the element is not needed in the model (e.g. when the dataset is stationary in the first-place, d value is 0). The middle element, d, is investigated before p and q. The goal is to determine if the process is stationary and, if not, to make it stationary before determining the values of p and q (Tabachnick et al., 2007).

Here, the weekly data of biomass commodity movement as well as data of biomass-fuelled electricity generation are prepared for the dataset for ARIMA modelling as shown in Figure 81 and Figure 82 (plotted for 104 weeks/two years uninterruptedly since usually for a time series analysis, the longer the time period the more accurate the analyses). For the identification step of the ARIMA modelling, the question of whether mean and variance of these datasets being constant over time needs to be addressed (i.e. is the mean apparently shifting over the time period? Is the dispersion increasing or decreasing over the time period?). If the mean is changing, the trend is removed by differencing once or twice. If the variability is changing, the process may be made stationary by logarithmic transformation. However, differencing the scores is usually the easiest way to make a nonstationary mean stationary (flat) (Tabachnick et al., 2007). So here, after observing the original dataset, IBM SPSS is used to make the processes stationary by removing any linear trends and producing a plot of lag 1 first differences as shown in Figure 83 and Figure 84. The observations in the four figures indicate that it is reasonable to assume that the commodity and electricity data can be considered already stationary and hence d=0 would be appropriate. This assumption is confirmed using the expert modeller feature in SPSS that suggests ARIMA components for a certain dataset. However, at this identification stage, it is worth considering that d=1 might be also acceptable, but the decision regarding this component can be decided at later stages when the decision about the fit ARIMA model is confirmed through estimation and diagnosis. Natural log transformation to remove changing variation from the first difference variable has not appeared to change the observations massively and hence such a transformation is neglected for the dataset (as it is not needed). Note that for this analysis it is assumed that weekly-based data is appropriate as a week provides sufficient granularity to demonstrate lagged data, and there would be no further benefit in analysing data for any finer granularity such as a daily-based which is considered as too finite to express any seasonal or periodic effect.

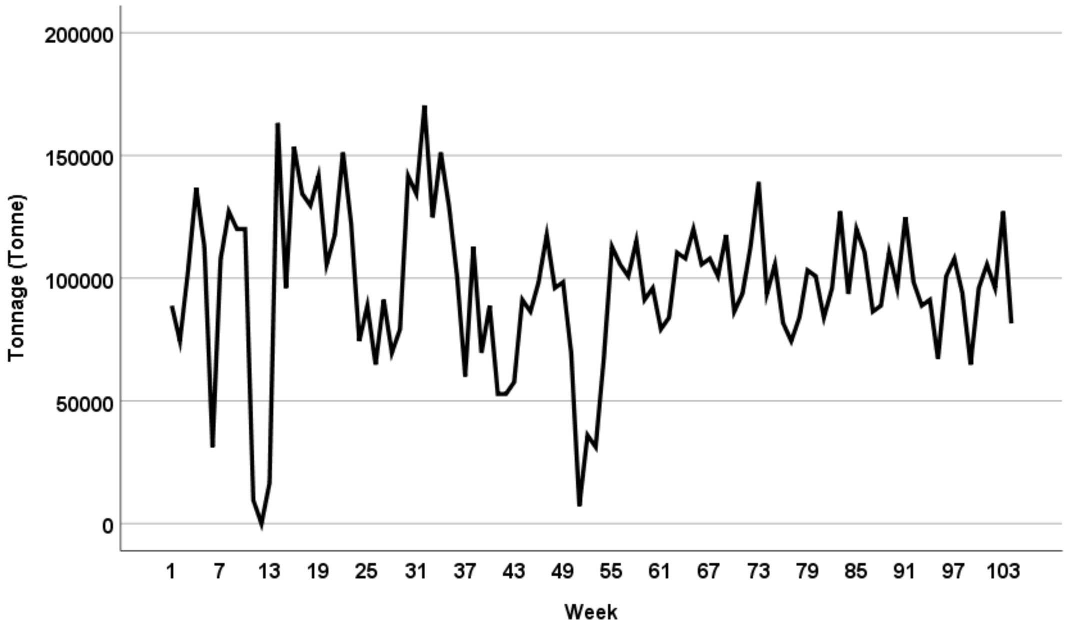


Figure 81 Biomass commodity moved in 2017 and 2018 on a weekly basis

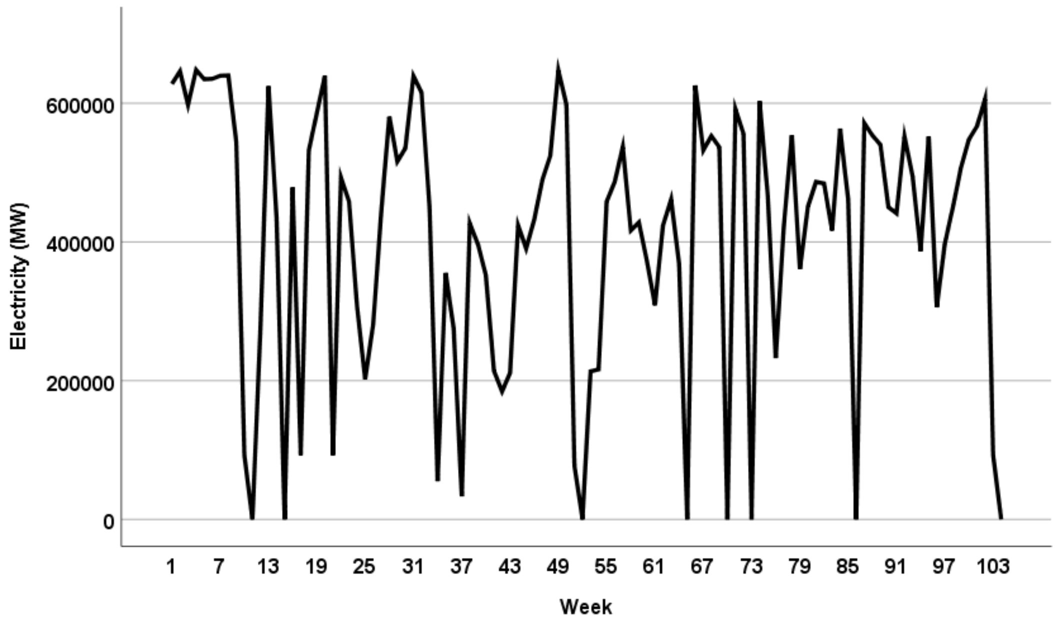


Figure 82 Biomass-fuelled electricity generated in 2017 and 2018 on a weekly basis

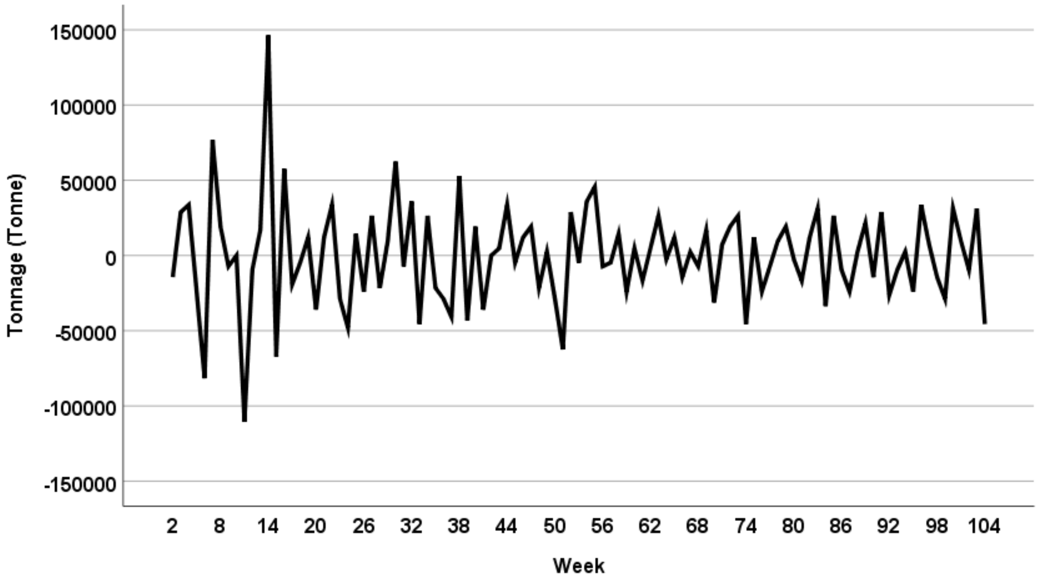


Figure 83 Plot of lag 1 first differences against a week for the data of Figure 81 (Biomass commodity moved in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

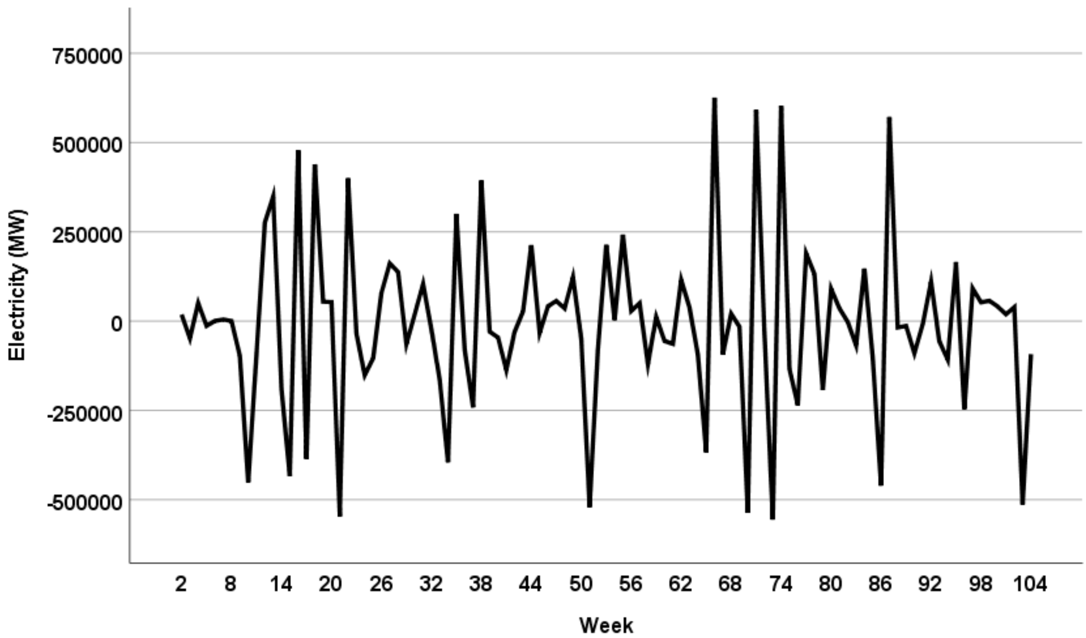


Figure 84 Plot of lag 1 first differences against a week for the data of Figure 82 (Biomass-fuelled electricity generated in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

Next, to determine the other ARIMA parameters; p and q, the dataset variables need to be assessed for the elements of autoregressive and moving average processes by jointly using a correlogram of ACF (Auto-Correlation Function) and PACF (Partial Auto-Correlation Function). Note that the autoregressive component represents the memory of the process for preceding observations. The value of p is 0 if there is no relationship between adjacent observations and when the value of p is 1, there is a relationship between observations at lag 1. On the other hand, the moving average components express the memory of the process for preceding random shocks. The value q shows the number of moving average components in an ARIMA (p, d, q) model. When q is zero, there are no moving average components. When q is 1, there is a relationship between the current value and the random shock at lag 1 (Tabachnick et al., 2007).

To determine the p and q components of the ARIMA model, patterns of both ACF and PACF of the dataset need to be assessed. Correlograms are plotted for both commodity and electricity variables of first differences using IBM SPSS as shown in Figure 85, Figure 86, Figure 87 and Figure 88. ACF and PACF diagrams are plotted for all 52 lags however usually the pattern of the first few lags would suffice to compare these obtained plots with standard, and somewhat idealized patterns that are shown by various ARIMA models - provided and thoroughly discussed by Tabachnick et al. (2007). Here, the pattern for commodity/tonnage datasets indicates a decaying ACF and a large negative PACF in the beginning, while the pattern for the electricity indicates a large, negative autocorrelation at lag 1 and a decaying PACF. Hence for the commodity, factors of the ARIMA model are suggested as p=1 and q=0, while for the electricity an ARIMA p factor of 0 and q factor of 1 could be suggested, as illustrated and elaborated in the source handbooks such as Tabachnick et al. (2007). Therefore, for commodity movement and electricity generation it could be assumed that ARIMA models of (1,0,0)/(1,1,0) and (0,0,1)/(0,1,1) are identified respectively. Using the expert modeller feature in IBM SPSS confirms the appropriateness of d=0 over d=1. However, whether these ARIMA models properly fit the actual observations or not need to be investigated and decided at a later stage by trial and error.

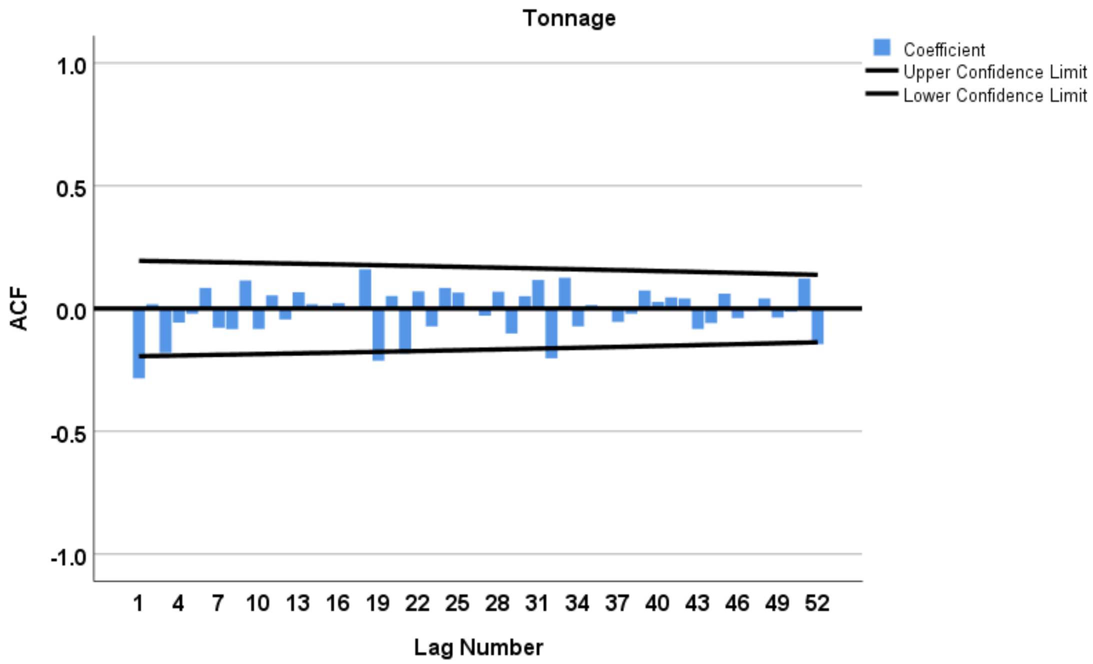


Figure 85 ACF for the data of Figure 79 (Biomass commodity moved in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

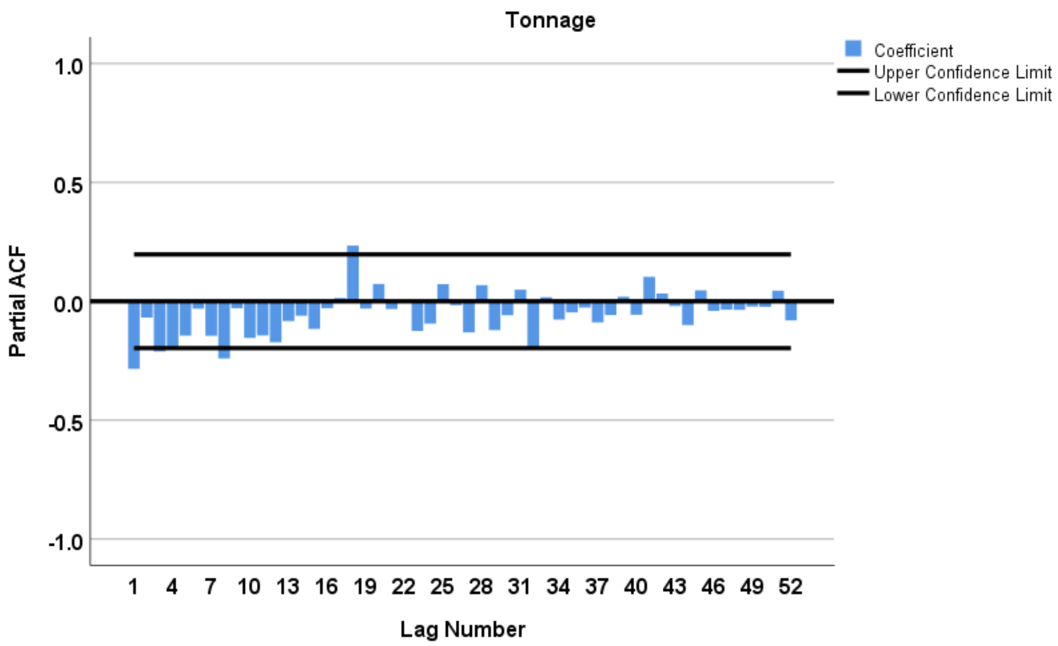


Figure 86 PACF for the data of Figure 79 (Biomass commodity moved in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

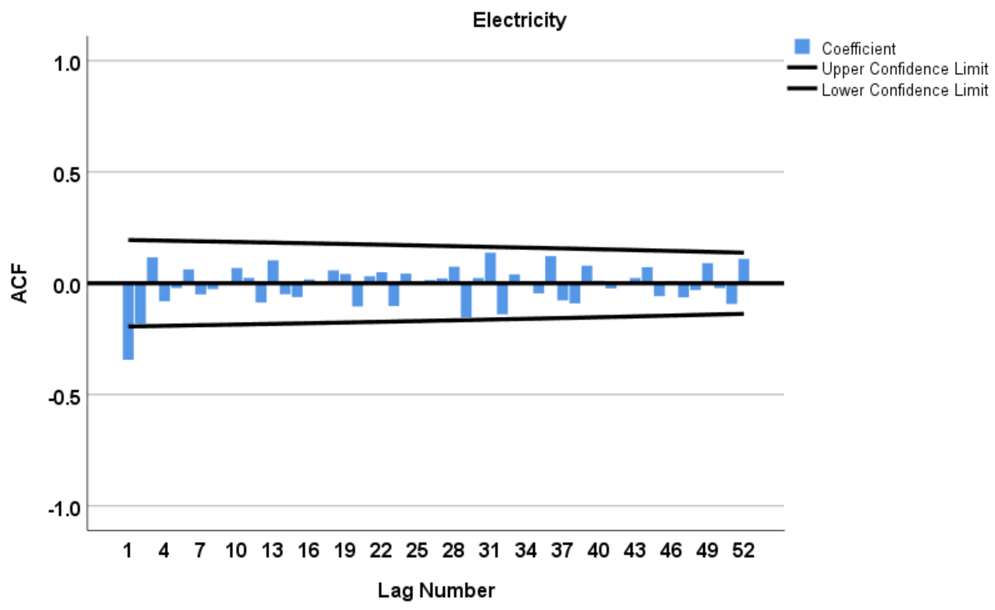


Figure 87 ACF for the data of Figure 80 Biomass-fuelled electricity generated in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

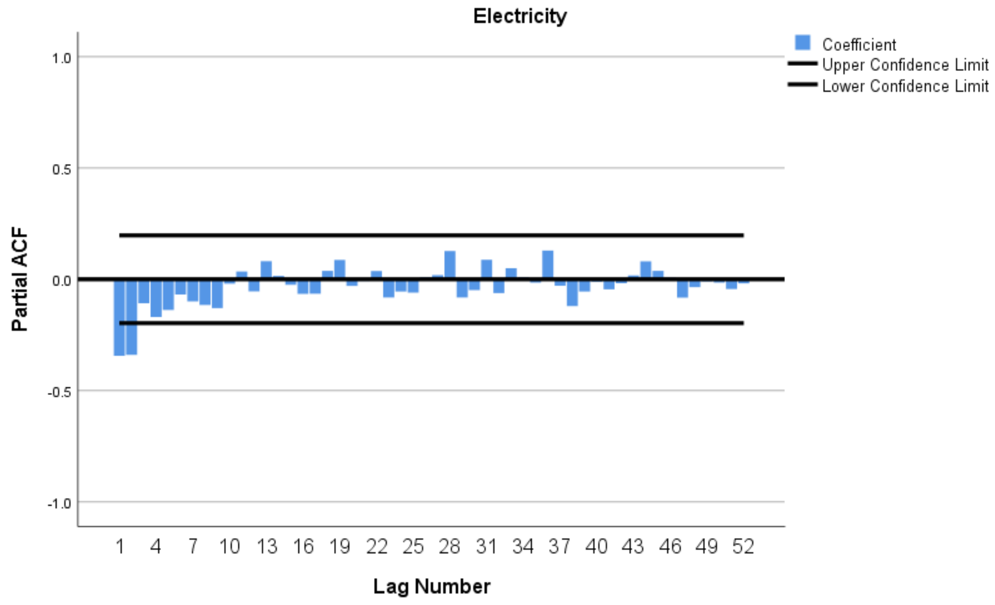


Figure 88 PACF for the data of Figure 80 Biomass-fuelled electricity generated in 2017 and 2018 on a weekly basis) produced by IBM SPSS TSPLOT syntax and output

After discussing and identifying reasonable assumptions for the ARIMA model, finding the optimal ARIMA model and deciding whether such assumptions result in the best fit or not is investigated using IBM SPSS. If the model is fitting/good, the residuals (differences between actual and predicted values) of the model are a series of random errors. These residuals form a set of observations that are examined the same way as any time series. Also, the smaller the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) the more fitting the model (Tabachnick et al., 2007). Additionally, where the observed/actual plotted graph appears to be closer to the fit plot, the ARIMA model is considered as optimal. For both commodity/tonnage, different ARIMA parameters were tested through a trial and error according to the above-mentioned criteria (as well as considering the analyses of components in the identification stage) and as indicates ARIMA (1,1,1) is known to be the most optimal fit that can be effectively used for forecasting future behaviour. This shows that:

- The commodity movement process and the electricity generation process could both become stationary (eliminating any moving mean) by differencing the processes only once.
- There is a relationship between observations at lag 1 (one week) for both processes and hence they have memory for preceding observation.
- There is a relationship between the processes' values and the random shock at lag 1 (one week).
- It is possible to forecast future values of biomass commodity movement and biomass-fuelled electricity generation based on the past values using an ARIMA (1,1,1) model.

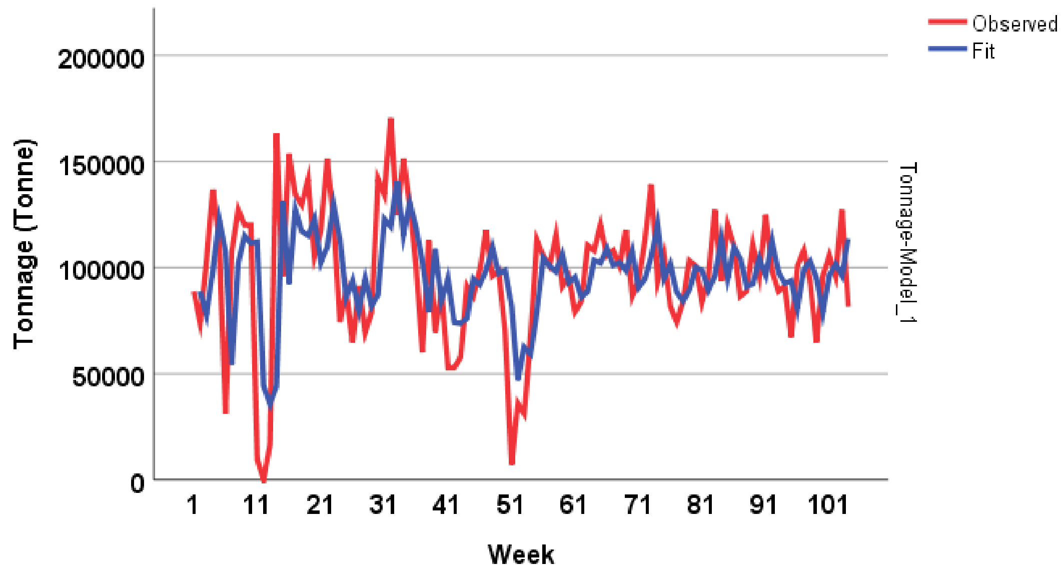


Figure 89 Observed values of biomass commodity movement in 2017 and 2018 on a weekly basis and fit values as predicted by ARIMA (1,1,1) model

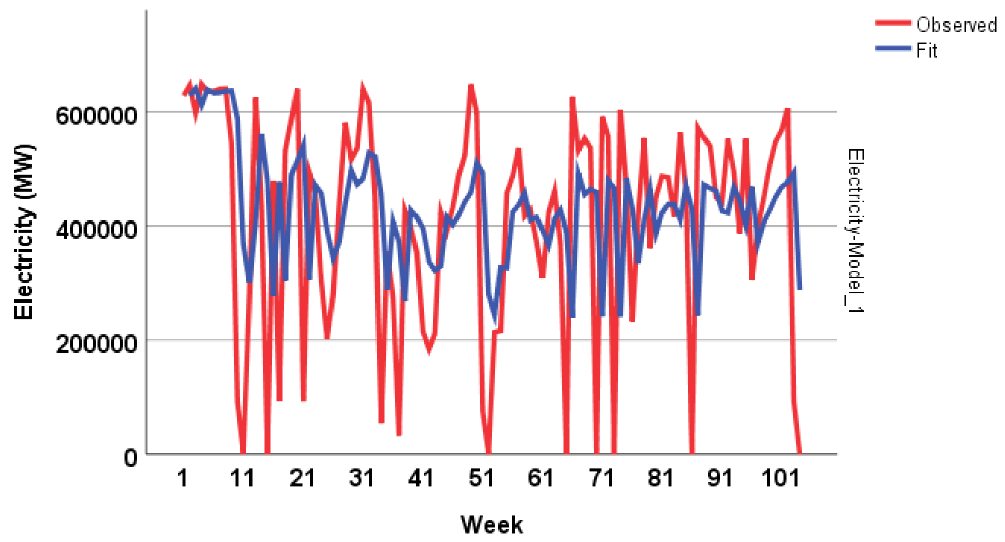


Figure 90 Observed values of biomass-fuelled electricity generation in 2017 and 2018 on a weekly basis and fit values as predicted by ARIMA (1,1,1) model

Note that as the main goal of fitting a time series into an ARIMA model is generally to understand the current behaviour and predict the future behaviour of that time series where required, however, this section only analysed biomass-related datasets. As the available coal data for two years could not be perfectly assumed as reliable to exhibit a proper time series (due to change of fuel source or lost data) there would be no benefit in investigating a fit model for them.

4.7.7 Estimation of stock level

Investigating commodity movement and electricity generation relating to biomass (in sections and 4.7.3 and 4.7.3) showed that on average, each tonne of biomass generated usually between 6 to 7 Megawatt of electricity in Drax (say the accurate conversion factor $\alpha = 6.452326782$ as previously explained in section 4.7.3). Note that this is the observed figure according to the overall two-year weekly average value and although it is considered as a reasonable assumption for this case study it cannot necessarily be generalised (i.e. such figures vary largely between power plants depending on their processes and working hours).

Therefore, using the available weekly data of power generated at Drax and roughly assuming $\alpha = 7$, the required amount of biomass commodity can be calculated. Figure 91 shows that over most weeks of the two years 2017 and 2018, the amount of moved biomass commodity inaccurately equals the amount needed at Drax for electricity production during the same week. Although the general pattern of both datasets is similar, the behaviour of transported commodity varied in time in relation to the required commodity during each week. For instance, for most of the weeks between week 15 to 22, the transported tonnage exceeds the required tonnage (except for week 20). However, the variable level of transported commodity suggests that the power station consumed the stored commodity that had arrived there between 7 to 10 days beforehand.

Note as there is no data or information available regarding the stock at day zero. Also, using the current data (i.e. not considering efficiency, processes and waste amount etc.) it is not possible to investigate the actual amount of stock being stored daily or weekly in the power station. However, subtracting required tonnage per week from the available (transported) tonnage per week can provide the pattern of stock level change over time, as shown in Figure 92. Note that the negative values at certain weeks show the power station consumed more biomass than it received during those weeks. As the figure shows, such a situation happened usually after the power station received more commodity than required and hence stored the excess (e.g. week 87). In general, the mean of the stock level is calculated as 4975 tonnes per week (i.e. provides roughly 35,000 MW electricity while the average weekly production at Drax is above 400,000

MW electricity) which is relatively a very low stock level. This shows that except for when the stock level is exceptionally high to compensate for the future low stock, the power station may consume most of its biomass stock in a week.

Furthermore note that the estimated stock level can be adjusted according to the information provided by the analysis of the daily data as presented in Figure 69 and Figure 70. It is reasonable to assume that sometime between weeks 10 to 12 in 2017 (corresponds with days 65 to 89 when the inflow or the outflow was 0), the stock went to 0. Hence, assuming the negative value of stock at week 12 (i.e. roughly -40,000 tonnes) as 0 in the adjusted figure, all other estimated values could be shifted up accordingly to present a more realistic view of estimated available weekly biomass stock at Drax.

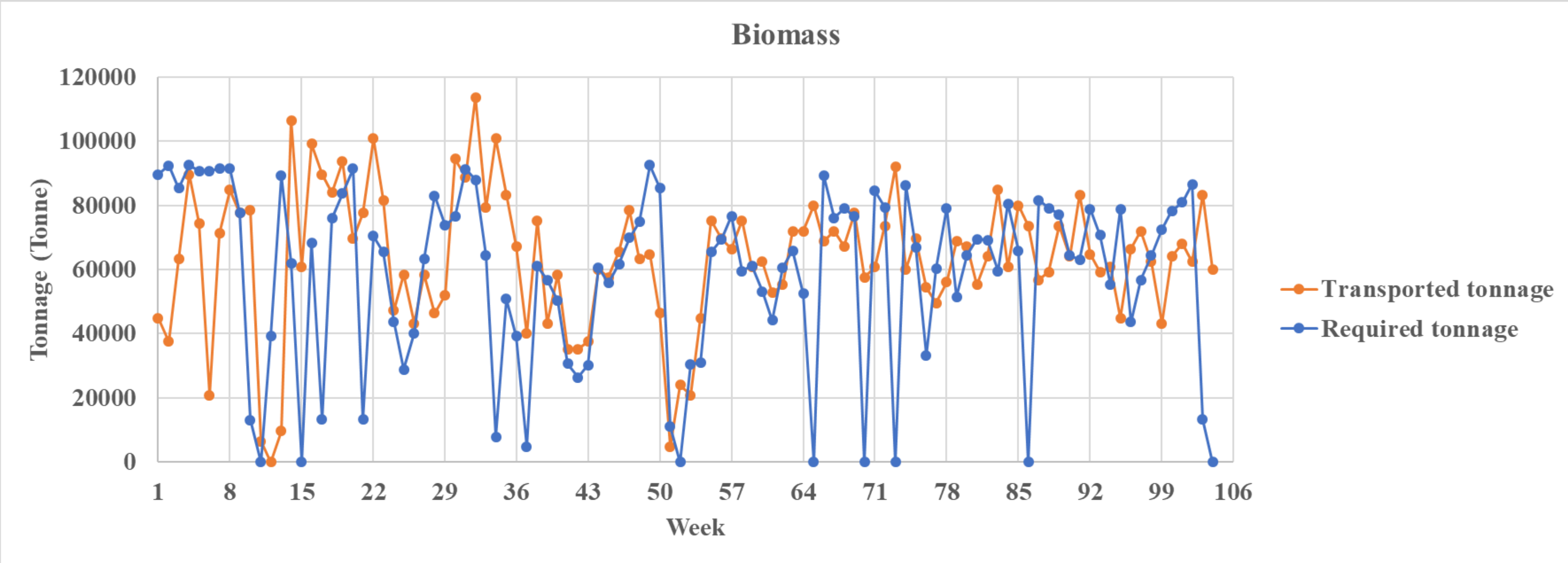


Figure 91 Comparison of the biomass commodity moved/transported to Drax and the required commodity for electricity generation during 2017 and 2018 (weekly basis)

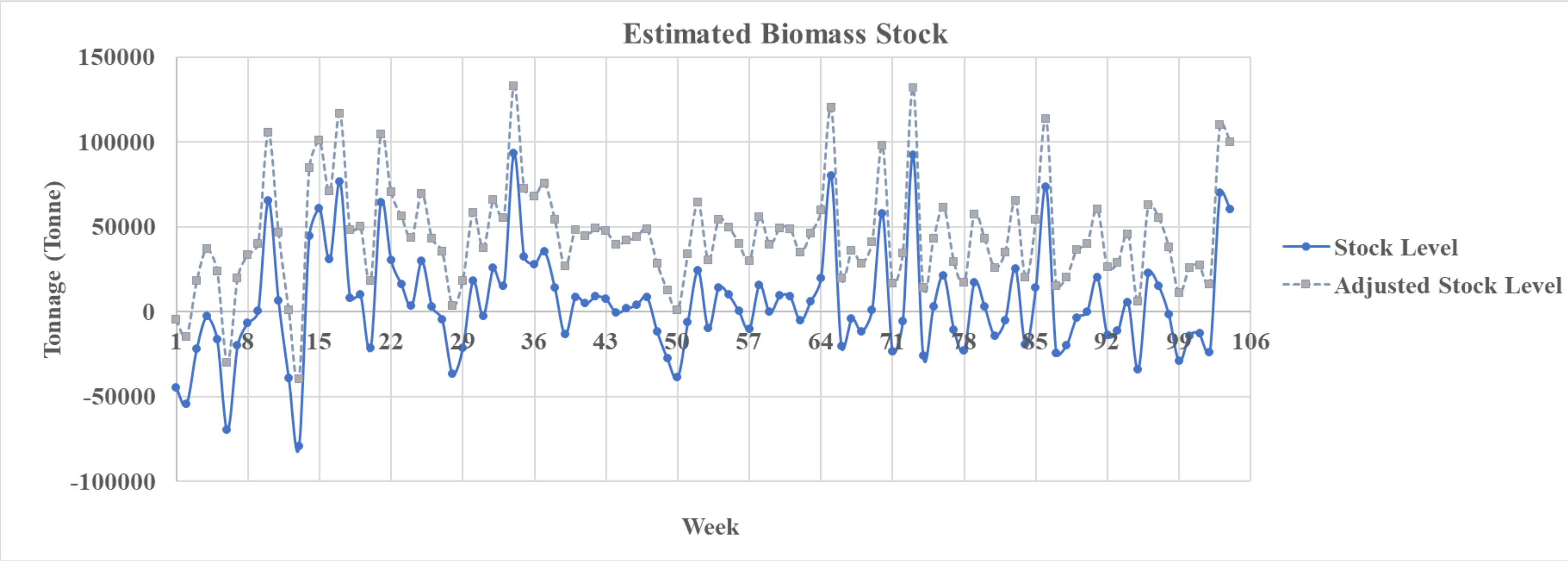


Figure 92 The biomass stock level at Drax during 2017 and 2018

4.7.8 Estimation of shock absorption threshold

This section explains the concept of sufficient stock level for variation and shock absorption and investigates a threshold for going out of biomass stock according to the analysed data and information collected through engaging with stakeholders.

Focusing on the concept of commodity inflow and commodity outflow (refer to Figure 45), Figure 93 shows a schematic representation of the average stock received by the power station as well as the stock level available at the power station. The generated electricity can be considered as the outflow from the power station which can be expressed using the same unit as used for inflow and stock (e.g. tonne). It is assumed that the inflow equals the outflow and both inflow and variations of inflow and outflow, are represented as their standard deviations.

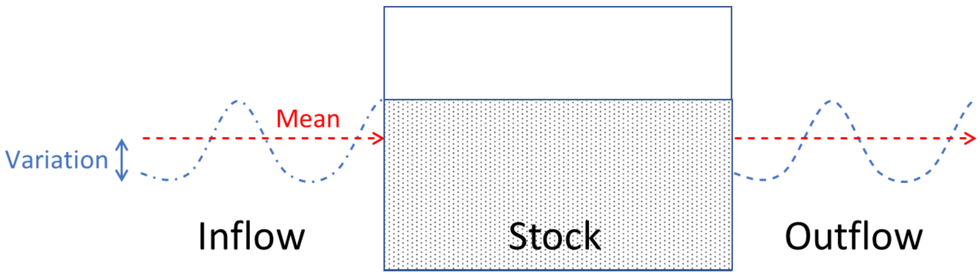


Figure 93 A schematic representation of commodity flow between railways and power stations

For the purpose of this analysis, it is also assumed that the variation in the inflow is totally independent of the variation in the outflow because the outflow variations ($SD_{outflow}$) can be mainly due to different situations of electricity demand and operations of the power station, including; seasonal electricity demand, planned closures, maintenance work and unexpected disruptions for the power plant. Whereas the inflow variation (SD_{inflow}) may be related mainly to the railways, including their planned engineering works, staff availability, closures etc.

Furthermore, it is assumed that the stock at power stations can act as an absorption buffer of disruption (or shock) for the interdependent systems in the case study area. Therefore, this thesis argues that the variation of the flow of this system (as shown in

Figure 93) can be considered as a sum of the standard deviation of inflow and the standard deviation of outflow.

It is assumed that the stock at the power station is used to absorb 1) the variation which relates to variation from the average operation condition (according to the available two-year data), and 2) the variation caused by any disruption (e.g. due to a massive flooding event) which was not observed within the two-year period. This suggests that the stock available for any disruption which was not observed within the two-year period can be calculated as:

$$Stock_{for\ potential\ disruption} = Stock_{total} - Stock_{for\ variation\ of\ average\ operation\ condition} \quad 4.1$$

Next, to calculate how long the power station could continue to generate electricity if 1) a disruption happens, and inflow stops or 2) the power station keeps generating using the stock, the following equations are proposed. This number could be used as a threshold to evaluate disruption. Hence, the threshold can be calculated as:

$$\text{Threshold} = \frac{Stock_{for\ potential\ disruption}}{Average\ daily\ outflow} \quad 4.2$$

$$= \frac{Stock_{total} - Stock_{for\ variation\ of\ average\ operation\ condition}}{Average\ daily\ outflow}$$

$$= \frac{Stock_{total} - [SD_{daily\ inflow} + SD_{daily\ outflow}]}{Average\ daily\ outflow}$$

Unit:

$$\frac{Tonne}{Tonne/day} = day$$

Table 31 shows the daily average value of biomass commodity moved as well as the biomass-fuelled electricity generation from the beginning of 2017 to the end of 2018. The data used here is the same as the one for Table 29 (related to the whole two-year period) but the mean and the standard deviation are for a daily basis.

Table 31 the values of the mean and standard deviation of inflow of biomass and outflow of biomass-fuelled electricity for the two-year data (daily basis)

	Two-year data (2017 and 2018)	
	Inflow (Tonne)	Outflow (Tonne)
Mean	9060.82	9060.82
Standard deviation	5915.39	3492.70

In terms of the total stock size, the experts stated that usually the stock level at the power station equals the weekly average value of commodity moved to the power station (refer to section 4.6.2.8) and that is assumed to be 63584.62 tonnes as shown in Table 29 .

Hence, according to equation 4.2, the threshold can be calculated as

$$Threshold = \frac{63584.62 - (5915.39 + 3492.70)}{9060.82} = 5.98\ days$$

The above calculation shows that the size of the stock which can be used during a disruption is equivalent of 5.98 ≈ 6 days of stock. This can be an estimated disruption threshold for the railway that supplies biomass (a perishable commodity) for electricity generation and can show the level of flexibility the power station has in terms of the number of days it can keep generating electricity with the current amount of stock. This threshold supports the understanding of the current inflow and outflow variation against the available stock at power plants as well as the vulnerability of the supply chain.

4.8 Summary and discussion

This section provides a summary and discussion concerning the findings, the approaches and the framework used in this chapter. The results of analysing the dependency between the freight railway and the power station in the case study area, as well as the suitability of the approaches used for the case study are summarised and discussed.

4.8.1 Summary and discussion of findings

This section highlights the main findings regarding the dependency scenario and the quantitative results and evaluates the qualitative findings based on the quantitative results.

4.8.1.1 The context of the dependency scenario

The existing literature as well as government reports (in sections 4.1 and 4.2) indicates a transition strategy from fossil fuels to renewable energy sources such as biomass. In the UK, some coal plants have been closed or converted to biomass plants and it is expected that coal will be gradually completely replaced by biomass. Nevertheless, in the UK both coal-fuelled and biomass-fuelled power production largely depends on freight railways, while commodities are mainly imported through ports. As for the degree of dependency/coupling of one sector on another, the academic literature indicates that a coal-fuelled electricity power plant is only loosely dependent on freight railway, as usually an adequate stock of coal is available at power stations (e.g. Rinaldi et al., 2001 in section 4.2). The degree of such dependency has only been evaluated qualitatively in the past and not quantitatively. Also, no effort has been observed within the available literature or among industrial practitioners to attempt to clarify the existing dynamics between interdependent sectors and later to collect, analyse and correlate the data related to sectors (e.g. freight traffic data and electricity power production). Factors such as the dependencies between interconnected sectors and potential vulnerabilities due to the type of stock in the supply chain have been largely ignored. Therefore, acknowledging the strategically important existing dynamics between transportation and ESI, while observing previously mentioned gaps of knowledge, motivated an academic investigation of local and engineering dependency for railways.

This research focused on the unidirectional dependency of electricity supply on commodity movement through freight railways as the only supplier within both the context of current dynamics and potential vulnerabilities. Consequently, several concerns have been identified and later addressed in this chapter. These concerns can be classified as follows:

- The little-known unidirectional flow of commodity supplied by railway for electricity production. This concern led the research to improve the understanding of overall interaction of several infrastructure systems in the electricity supply chain as well as finding the details of the dependency scenarios such as the operational thresholds during disruptions using the knowledge of experts (see sections 4.6 and 4.7),
- Vulnerabilities or risks that can cause disruption to the commodity supply with a focus on supply chain risk from the viewpoint of freight railway as the main and single supplier. This concern led the research to improve understanding of important railway-related vulnerabilities that can potentially create significant disruptions and cause paramount impacts on other infrastructure systems (see section 4.6),
- Potential impacts on the downstream of such supply chains which led the research to investigate potential disruptions of the electricity generation due to railway traffic disruption (see section 4.7) and
- The flexibility or shock absorption of the dependent infrastructure system (i.e. ESI through electricity generation). This concern led to analysing the variability in usual operations (refer to sections 4.7.3 and 4.7.3), delay factors (section 4.7.5), the dependency between commodity supply and electricity generation (section 4.7.6), variability of stock levels (section 4.7.7) and shock absorption thresholds (section 4.7.8).

Note, consulting experts showed that employing a case study approach towards investigating local and engineering cross-sectoral scenarios, is an effective method to exemplify and explain infrastructure dependencies, because it provides a realistic basis for the research. Consequently, both qualitative and quantitative analyses produced invaluable outcomes for the research including; improved knowledge and evaluation of little-known railway infrastructure dependencies. Figure 94 summarises the gaps, the analyses and the outcome of investigating the dependency between electricity generation and freight railway in the case study area.

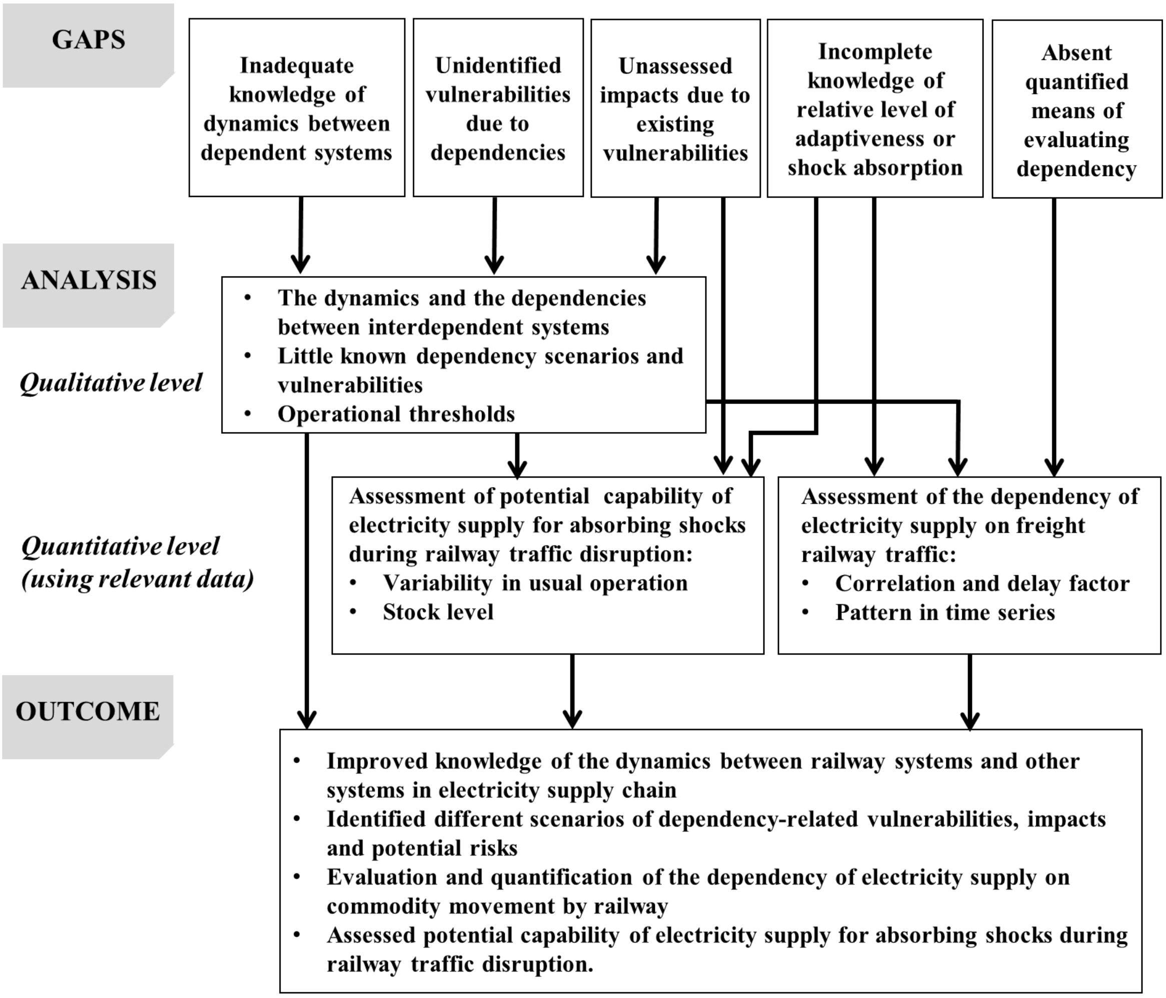


Figure 94 Summary diagram of investigating dependency of electricity generation on freight railway in the case study area

4.8.1.2 Quantitative findings and discussion

Regarding the elements of the quantitative analysis, this chapter used actual and quantitative data from a power plant and its supply of fuel, using freight traffic to describe the dependency of electricity power production on railway freight traffic. The data was mainly obtained from two sources: TRUST data of Network Rail and publicly available data for electricity production and were investigated at different units of time depending on the purpose of each analysis (e.g. daily, weekly and monthly) . Several stages of analysing the data and interpreting the dependency have been developed: visual investigation of the variability in time (in section 4.7.3), descriptive statistics (in section 4.7.3), time series analysis; autocorrelation (in section 4.7.5) and ARIMA modelling (in section 4.7.6), simple correlation using the Pearson correlation coefficient (in section 4.7.5), investigating the stock level (in section 4.7.7) and estimating a threshold for shock absorption (in section 4.7.8).

The qualitative approach could effectively evaluate a little-known dependency where railways are the sole mode of transport for supplying perishable commodity for ESI. Combining the different stages of quantitative analysis along with the information obtained through the engagement with stakeholders the following conclusions can be made regarding the commodity flow level of the case study:

- It has been found that the nature of freight traffic for ESI (known as inflow in this case study) is highly dynamic and that the outflow is very demand related. This is shown in sections 4.7.2, 4.7.3 and 4.7.4 through consulting experts. The number of coal trains varied from 0 to above 40 per week, while the number of biomass trains varied from 0 to above 70 per week over the two years.
- The visual analysis showed how the supply and the production behave over time and whether they have a similar trend or not, whereas the descriptive statistics effectively demonstrate the measures of central tendency and measures of variability (spread). The analysis showed that the inflow and outflow expressed a very similar trend for biomass (in section 4.7.3) while no similarity in trend was observed regarding coal. Furthermore, seasonality was observed for power generation in general (a combination of coal-fuelled and biomass-fuelled energy at Drax and the total energy at National Grid) (in section 4.7.3). However, the inflow and the outflow of coal did not necessarily show a seasonal or repeating pattern. This indicated that; firstly, the coal can be easily stocked and only used when demanded, and second, the coal inflow usually depends on the market price (see sections 4.7.3 and 4.7.4).

- The daily analysis in Section 4.7.3 and the examination of zero days (e.g. during planned closures) showed that the biomass is supplied about one week in advance. It is also argued that although railway traffic was limited during weekends, the generated electricity was fairly consistent for all days of a week. For instance, the distribution of daily averages along different days of a week showed that for biomass, a minimum average of 51485 MW on Sundays of 2018 and a maximum of 63786 MW on Mondays of 2018 were observed. The two-year data is not necessarily indicating any specific pattern for the sum and average of generated electricity during a week. Additionally, the electricity generation increased during colder times of the year (refer to section 4.7.3).
- Section 4.7.4 showed that for the biomass commodity, an average of between 5 to 6 trains per day moved to the power station in 2017 and 2018 with a standard deviation of almost 4 trains and 3 trains in 2017 and 2018 respectively. These figures indicate the popularity of biomass as an energy source in Drax (compared to coal). Moreover, a fairly regular pattern was observed for the inflow of biomass and the outflow related to both biomass and coal. It was also found that during a week the railway could be capable of accommodating 14 biomass trains in addition to the average/usual number of trains (i.e. 40 trains). This could be explained through the seasonality characteristics of the outflow.
- Additionally, correlation and autocorrelation showed whether there was any direct connection between the supply and the production by looking at the individual behaviours over time, while ARIMA modelling can successfully describe the patterns over time and provide a means for prediction of future values (sections 4.7.5 and 4.7.6). Autocorrelation and Pearson correlation both gave the same conclusion that there was no tight dependency between coal supply and power production, as the coal inflow and outflow expressed no specific pattern over time. This was clearly shown in the autocorrelation through fast dying correlation curves in which the data forgets itself in a short time (i.e. random behaviour of the data). However, for the biomass supply there was a clear similarity between the two autocorrelation curves showing a strong dependency between them (i.e. periodic behaviour of the data). When directly calculating the correlation between the supply and the energy production using the Pearson correlation method, the same behaviour has been observed as the

value was smaller for coal-related data (0.1) compared to that of biomass (0.35).

- It was possible to forecast future values of biomass commodity movement and biomass-fuelled electricity generation based on the past values using an ARIMA model (in section 4.7.6). The data related to biomass expressed a memory for preceding observations at lag 1 and hence it would be possible to forecast future biomass inflow and outflow based on the past values using an ARIMA (1,1,1) model.
- Analysing biomass stock levels at the power station (in section 4.7.7) showed that for biomass, the transported tonnage roughly equals the required tonnage in a week. This means that usually weekly biomass stock may not be very large, which may result in vulnerability of production and little capability of ESI for shock absorption if dependency on biomass-fuelled electricity increases (while the storage challenge remains).
- The vulnerability of shortages due to the complexity of perishable commodity supplies by rail can be effectively evaluated as shown in section 4.7.8. It can be argued that currently the power plant would be able to safely operate for approximately only 6 days (and not further) during disruptions. This may represent an operational threshold and is based on the information collected through stakeholders who stated the power plants usually have an equivalent of one week of biomass stock. Note that every dependency scenario within the context of vulnerability mentioned in section 4.6.2 can be treated as a disruptive event that may interrupt the usual commodity inflow. Such scenarios can be analysed individually in further research studies to evaluate their impacts on the power plant considering the calculated operational threshold in section 4.7.8.

Therefore, the following arguments can be made as per the results of the quantitative analysis in combination with the knowledge that experts shared:

- Regarding coal as the fuel for electricity production, it can be argued that, the electricity generation and rail transport are not tightly related to each other. Although there exists a loose dependency as the coal commodity is easily stored, the power station piles up the stock potentially when coal is cheap on the market. It is reasonable to argue that the dependency between electricity generation and rail transport is less time-lenient and hence the coal-fuelled electricity generation would be resilient during shocks (unexpected disruptions). Although there is a possibility that long lasting disruptions happen when coincidentally there is little coal stock available. As the coal will be gradually replaced by biomass in the UK, it is argued that the current coal supply chain for ESI acts more like an alternative strategy when the biomass-fuelled generation alone cannot meet the electricity demanded by National Grid.

- Regarding biomass as the fuel for electricity production, it is argued that the electricity generation and rail transport are tightly dependent on each other as the inflow resembles the outflow pattern by a one-week lag. It is also argued that a lean supply chain behaviour is observed since the daily variations are relatively small (the power production is not significantly volatile on a daily basis), and the power station may use the commodity transported to it during a week in 7 to 10 days to decrease the cost. The biomass-fuelled electricity generation is vulnerable to fail to generate its average daily electricity if any event causes more than 6 days of consecutive disruption to the supply chain. This is because almost 1 day of stock is used to absorb the daily variations from inflow and outflow and hence, the shock absorption threshold (level of buffer) is 6 days if the stock at the power station is equivalent to the average of one week of stock.

- As for the comparison between coal and biomass as the main commodities for generating electricity in this case study, it can be argued that ESI is more vulnerable to have a shortage of biomass-fuelled electricity and less vulnerable to coal-fuelled electricity. This is because currently the power plants can more easily stock coal for a relatively very long time while the lean or continuous coal supply management remains a challenge.

Table 32 summarises the dependency scenario statements that are found as the result of the evaluation carried out in this chapter. Note these statements are considered as a beneficial contribution to the conceptual literature (section 2.1.1) that showed a lack of any kind of comprehensive picture of railway infrastructure dependencies (e.g. with power infrastructure).

Table 32 The conventual dependency statements related to the scenario of commodity supply by rail for power production

The dependency statements	Operating condition	The dependent/interconnected infrastructure systems/sectors
The supply of commodity for power production through rail traffic is dynamic in nature. This is because of the industry practices such as; low traffic flow during weekends and holidays, variation of staff availability and frequent engineering works (maintenance activities) that require railway line closures.	Normal	Railways and Power production
The behaviour of power production at power plants depends on the national demand (i.e. seasonal) and strategy (e.g. biomass-fuelled energy is favourable to coal-fuelled energy but when power plants cannot meet the demand, they use coal as an alternative).	Normal	Power production and National electricity production
The commodity flow between railways and power production systems express different behaviours based on the type of the commodity involved in the supply chain. The supply needs to be frequent for the perishable commodities that cannot be easily stored regardless of the market price. However, the storable commodity is bought and supplied when its market price is low.	Normal	Railways, Power production and National electricity production
Where the commodity (i.e. fuel) is perishable and there is no long-term storage solution, a tight dependency exists between the rail traffic and power production. For instance, in the case of biomass in the case study area, the electricity generation follows the biomass commodity movement pattern in a periodic manner with a one-week lag (i.e. the biomass is supplied one week	Normal	Railways and Power production

in advance). A lean supply chain behaviour in which cost is minimised is observed for the dependency scenario in this case.		
Where the commodity is easily storable (e.g. coal) while at the same time it is not the favourable fuel for the power production, its movement (through rail) is quite random and dependent on various factors such as the market price.	Normal	Railways, Power production and National electricity production
During colder seasons railways are vulnerable to disruptions (due to flooding, poor sight, ice on the rails and leaf fall) while at the same time, power plants increase their output. Hence, the dependency between railways and power production expresses a seasonal behaviour.	Disruption	Railways, Power production and National electricity production
Where railways are not the only mode of transport in the electricity supply chain (e.g. when commodity moves from ports to railways) the commodity supply and hence the power production can be affected by the disruptions at other modes of transport.	Disruption	Ports, Railways and Power production

4.8.1.3 Evaluation of qualitative findings according to the quantitative results

Regarding the findings through qualitative analysis (section 4.6), experts could significantly contribute to identifying the nature of non-evident infrastructure dependencies (from both normal and vulnerability viewpoints). The qualitative investigation supported the understanding of overall dynamics between sectors, potential significant risks for the railways and the dependent systems in the area, as well as understanding the details of the dependency scenarios such as the operational thresholds during disruptions.

When evaluating the findings in section 4.6.2 based on the results in section 4.7 the following conclusions can be made:

- The critical section in the case study area between Barnetby and Brocklesby can be considered as a major vulnerability for the supply of biomass to the power plant (refer to 4.6.2.1). If any structure within this area fails (e.g. a bridge or a culvert structure) or a landslide happens, the repair will normally take longer than a week which exceeds the threshold for shock absorption (calculated in 4.7.8).
- Regarding the flooding risk and secondary impact such as landslides, usually the disruption period is very long. As stakeholders argued, in a case of coastal flooding if a port terminal is damaged, it takes approximately 3 months for its repair. Considering the current biomass supply chain strategy, flooding is considered as a very high impact incident for ESI. The risk of flooding threatens not only the port facilities and the railway assets within the port premises but also railway lines in the area (refer to 4.6.2.2 and 4.6.2.3).
- Referring to section 4.6.2.4, as for the staff unavailability, it is evident that the electricity supply industry can easily absorb daily variations and hence small-scale disruptions cannot be viewed as a vulnerability. However, staff unavailability might happen as a secondary impact of larger-scale risks such as flooding that can have a serious impact on ESI. Moreover, as bridge strikes can potentially cause structural damage to the bridges in the critical section, it is considered as a major vulnerability that impacts the supply chain (as the repairs may exceed more than a week).

- As the quantitative results showed that the biomass inflow (and hence the related rail transport) is frequent and the supply is lean, the condition and monitoring of gradual changes along and near the railway premises is crucial (for water mains, geotechnical structures etc) (refer to section 4.6.2.5 and 4.6.2.7). Structural failures and flooding (e.g. due to a water main burst) that can close the critical area of the railway for more than 6 consecutive days can be considered as serious risks for the ESI in the case study area.
- As per section 4.6.2.6, because each coal or biomass freight train carries around 1,600 tonnes of coal or biomass, replacing trains with trucks would cause heavy congestion on the road network in the area and would have various adverse impacts including delays in the journeys of local commuters or blocked access to the port for other port users (e.g. trucks using ferry services). Therefore, road transport cannot be considered as a practical (and long lasting) option for the biomass commodity movement to power stations. This emphasises the tight dependency of power plants on rail transport where the commodity is perishable while its tonnage is very large.
- As the generic framework explained in Figure 30 showed, a quantitative analysis should satisfy/validate the qualitative information collected from experts. This has been thoroughly demonstrated in section 4.7 where the qualitative statement in 4.6.2.8 (with regard to the dependencies due to the type of commodity in the supply chain) has been evaluated using data and statistical analysis.

Note that, section 4.7 through quantification (using data analysis and modelling) could successfully satisfy the information collected through consulting experts (highlighted in 4.6). An example of this includes; the data could successfully demonstrate that infrastructure dependencies are tighter when the fuel is biomass compared to when the fuel is coal. This suggests the suitability of the generic framework in Figure 30 that described the first pillar of the research“ Information, Concerns and Needs” (or the mostly qualitative findings) supports and facilitates the second pillar of the research “Modelling, Analysis and Results” (or the quantitative findings). On the other hand, the second pillar also satisfies and validates the first one.

To summarise the overall findings in this section (0), considering the growing reliance of ESI on bioenergy (including biomass as the main fuel) and on individual major power plants for electricity generation, the energy supply chain can be considered as potentially vulnerable to running out of biomass stock. As the analysis conducted by this research showed a tight dependency between train movement/traffic and biomass-fuelled electricity generation, any threat that disrupts the normal operation of railways could be viewed as a potential vulnerability of power plants (and hence ESI) to meet electricity generation demand. Regarding this academically investigated dependency the following points need to be considered:

- At a detailed/commodity level, it is argued that currently ESI tightly depends on the railway system. This was explained through the one-week operational pattern observed in the analysed results (see section 4.7)
- Since the tight dependency (at a commodity level) results in vulnerability at an infrastructure level, it is recommended that such vulnerability needs to be considered for supply chain risk management.

Note, in order to reduce the vulnerability for ESI, either better storage solutions need to be devised for commodities (to reduce the tightness of the dependency) or the resilience of transport needs to be improved as a long-term plan through; diversifying ports and railway lines, including other modes (e.g. canals for coal transport) and expanding the underlying infrastructure to improve the capacity etc. This is an example of how a scenario-based dependency investigation through case studies can produce recommendations for infrastructure systems at a sector or national and strategic level. The next section discusses the overall approach and framework used for the analyses in this chapter.

4.8.2 Summary and discussion of the approach

Regarding the approaches employed in this chapter, it is reasonable to conclude that overall, the elements shown in the two pillars of the generic framework (as shown in Figure 30) supported the investigation of a non-evident infrastructure dependency at a sector level. Using the opinion of experts to clarify gaps and to develop dependency scenarios (that were absent from academic literature) while simultaneously employing case studies to exemplify the investigation, facilitated quantifying a strategically important dependency scenario. Moreover, the quantitative analysis validated the qualitative information collected from experts.

Whereby the qualitative investigation helped to understand the overview of the existing interdependencies and the current dynamics between dependent systems, the quantitative investigation evaluated a critically important dependency against the current operation by analysis of the available data. Also, where individual contact and smaller engagement (e.g. one to one interviews) effectively allowed for the collecting and confirming of initial information (e.g. the criticality of the link between rail and power in the case study area), larger engagement sessions (e.g. through workshops) have supported quick and efficient collection of the consensus of opinions from experts regarding specific dependency scenarios. Note, the individual contacts could aid not only during data collection and scenario development/analysis but also before and after these phases including reviewing the existing knowledge, exploring proper methods and techniques as well as seeking and incorporating feedback. The practicality of such engagement can be traced in this chapter where critical information/data was provided, and important decisions were made through stakeholder engagement. Also, note, that none of the collected information/data through a participatory-based approach could be found with a high level of confidence using publicly available sources. This specifically applies to the input and details that trend, change or evolve over time and only day to day practitioners are aware of (e.g. difference in complexity of logistics for commodity movement and the future of supply for power plants).

Additionally, for this case study stakeholders could facilitate and accelerate research activities such as identifying more relevant stakeholders inside and outside their sectors and organising field trips and site visits which require access and related permits (e.g. railways site visit to visually inspect characteristics and vulnerabilities). On the other hand, although the fundamental purpose of doing academic research is to be adding to the body of knowledge for a specifically defined problem (i.e. a research question), employing a participatory-based approach could provide additional benefits such as finding numerous further gaps that potentially create research questions for future studies All the findings listed in section 4.6.2 (except 4.6.2.8 for which a quantitative analysis has already been conducted in this chapter) can potentially be treated as future academic research questions. Since a group of stakeholders have a relatively broad viewpoint towards gaps, even informal engagement with them can provide invaluable input for future research work. Some of the recommendations regarding further research for the qualitatively stated rail and power dependencies are summarised in section 4.9.

Lastly, regarding analysing the data related to sectors as the quantitative approach employed in this chapter (in section 4.7), it is argued that such analysis is essential to comprehensively interpreting the infrastructure dependencies. Different techniques (including statistical and time series analysis) employed to understand the data, need to be selected fit for the purpose such as for facilitating an explanation of the existing dynamics between sectors at different points in time. Evidently, both analyses of data and interpretation of the results required engaging with experts. For instance, the results could not be comprehensively interpreted if operational facts such as the estimation of stock, planned closures and trends such as diversifying ports of imports were absent from the investigation. Note that although the data and analysis techniques included limitations (i.e. model assumptions and lost data), they could successfully interpret the existing dependencies and dynamics between the sectors.

As shown, the sub-framework has been created based on the generic framework described in Figure 30 and includes the two elementary pillars as well as elements such as “scenario development”, “case study”, “data analysis” and “modelling”. The sub-framework (or the chain of logic) as illustrated in Figure 46, showed several characteristics which are explained as follows:

- Knowledge ordering/structuring and incremental scenario development: The sub-framework simplified the complex nature of an interdependency investigation by dividing the research question into two manageable levels. The two levels being infrastructure level and commodity flow level represent the low-resolution investigation (at a regional/national scale) and high-resolution analyses (at an engineering and technical/local environment). As section 4.6.1 showed, the stakeholders contributed to understanding of both the overall dynamics and patterns observed between the three sectors and details of the commodity movement (e.g. thresholds and stock level). Therefore, a comprehensive overview of the infrastructure dependency is formulated and specified incrementally.

- Signifying the focus/concern of the infrastructure dependency research: At a higher-resolution (detailed) level, the sub-framework directly focused on a unidirectional flow from railways to ESI through the commodity flow. As previously mentioned, the academic literature considered (but not quantified) characterising qualitative flow between railways and other systems in an over-simplistic manner (refer to Pant et al., 2016 and RSSB, 2016 summarised in section 1.2.2). However, in reality the nature of flows between sectors and how they are characterised should be largely inspired by the individual dependency scenario and the quickly evolving, highly complex nature of those sectors. As the sub-framework of this chapter signifies, the attention was drawn to the role of railways as the only major supplier for ESI and hence the measurable variables (e.g. electricity generation and stock stored) were evaluated against the commodity flow in the supply chains.

To conclude, it is argued that any similar framework which addresses concerns of experts by incrementally developing dependency scenarios at different scales and later characterises a flow between two or more systems by employing a quantitative analysis, can potentially facilitate the investigation of the various infrastructure dependencies. An example of such dependencies includes supply chain risks related to any commodity transported from ports to sectors such as; steel, oil, timber, minerals etc.

4.8.3 Limitations

There are some limitations of the current analysis and these are discussed below. First, the conclusion is based on only one case study for a single power plant and on the available data at the time of this study. In order to generalise the results and conclusion, more similar case studies could be used. The work of this thesis gives the basis for such data analysis. Also, the time length of the data should be sufficiently long. Indeed, the results would be more reliable if the data were available for more than two years (which was the time available for the analysis in this case study). In that case the variation of the seasons’ supply and demand could be more confidently included in the dependency study. Additionally, the coal commodity movement in 2018 as a dataset could not provide a strong basis to fully investigate the behaviour of coal-fuelled electricity generation. It is also worth mentioning that the study in this thesis considered the dependency between freight volume and power production from one power plant in isolation (i.e. assuming no effect of any other asset/condition). However, that is not 100% correct. For instance, the cost of the freight movement (energy efficiency and mileage travelled) could not be taken into account as an important factor due to a lack of data availability. The impact of many disruption scenarios which may happen during the course of two years could potentially be taken into account when giving an interpretation of dependencies. For the calculation of stock level, preferably further information such as energy efficiency and working hours of the power plant is required to conduct a proper correlation study between the stock and other factors such as traffic movement.

There are more factors that can be taken into account in dependency analysis in future research. For example, it is well known that the supply of coal is price oriented, meaning that power plants buy stocks of coal when it is cheap, while the supply of biomass is demand oriented; meaning that they buy it only when they need it (no stock). For this reason, the price of coal can play a major role in the dependency. The main reason for the tight dependency of the biomass-fuelled power production on biomass supply is the complexity of the storage. Thus, there is a need for storage capacity growth in the future and a potential for further research regarding this issue. It should be also noted that one of the main factors affecting power production at a power plant is the demand by the National Grid. This makes the subject of dependency between two sectors more complicated as there are many factors affecting the National Grid demand. Further case studies and more national scale database systems similar to the University College London’s Freight Train Movement Data System (FTDMS) can gradually pave the road for investigating the impacts of local and technical dependencies (e.g. the issue of a shortage of biomass) in regional and national scale analyses. Furthermore, although the effect of disruptions in electricity supply on passenger railway operation has been extensively studied in the past (e.g. Johansson and Hassel, 2010), the effect of such events on the mixed electrified passenger/freight railway path was ignored. Regarding future research, this topic can potentially be investigated in order to have a bigger picture of the dependency between two sectors.

4.9 Additional recommendations for further work

In terms of the non-evident dependencies which are investigated qualitatively (but not quantitatively) in section 4.6, deeper exploration is needed. This section provides some recommendations that act as a high-level guideline for further work in the field of little-known railway dependency scenarios.

For example, in terms of criticality of the components of a railway (or other dependent) system (refer to section 4.6.2) identifying and evaluating the vulnerability of railway assets at a regional or national scale could act as an initial step towards the further exploration of this dependency. Identifying the contribution of network components to network vulnerability is a well-studied problem in the reliability engineering literature (Whitman et al., 2017). When analysing a system's reliability and availability, measuring the importance of components can usually facilitate prioritizing improvement efforts regarding planning, operation and maintenance. In reliability engineering, Importance Measures (IMs) rank components according to their adverse effect on network performance when removed and hence are used to estimate the relative criticality of systems (Whitman et al., 2017). Such network performances could be evaluated with graph theoretic measures, such as average shortest path distance or closeness centrality (Dunn and Wilkinson, 2012 and Tizghadam and Leon-Garcia, 2008), or with flow-based measures, where the importance of a component is determined by how it enables flow in the network (Johansson et al., 2011 and Nagurney and Qiang, 2008). Whitman et al. (2017) analysed network vulnerability of Swedish rail as a multi-commodity network from a flow-based approach to identify critical links in the network. The data used was relevant to stations and movement of cargo as well as supply and demand parameters. The metrics such as unmet demand during a disruption indicated the criticality of nodes and links in the investigated network. Similar reliability engineering-based studies at a regional level for the UK multi-modal freight networks could provide beneficial further research in case of the dependency identified. Network-based and flow-based approaches in general are also capable of facilitating investigation into some other dependencies identified, which could be worthwhile to be perceived as a more regional or national dependency problem rather than a local one. Vulnerability of systems due to asset ownership issues and dependencies during emergency and recovery conditions are examples of such problems which were identified in this chapter. Furthermore, regarding the vulnerability of dependent systems due to environmental and climate-related aspects, similar approaches could be combined with other predictive methods. For example, using port of Immingham as a case study, French et al. (2017) used Artificial Neural Networks (ANN) to forecast extreme water levels and propagation of surges within estuaries and found this methodology effective and useful. Moreover, Jaroszweski et al. (2015) explored and quantified the impact of a notable storm on UK transport using previously underutilized transport data. The research showed how the failure of infrastructure at several locations of crucial importance can effectively block access to different parts of a country by certain modes of transport and cause knock-on delays that can propagate throughout the national transport system. Further research is necessary to correlate other extreme events with the knock-on effects on the critical infrastructures.

Regarding dependencies relating to people, the current knowledge regarding intermodal passenger transport, an end-to-end passenger experience for road and rail, as well as the risk of railway bridge strike is very limited. Initial steps are required in order to carry out surveys and collect statistics and spatial/temporal data regarding many factors including; the mode of transport used by railway staff, the length and time of their travel, allocation behaviour and future challenges (e.g. social and demographic changes in a region) would act as initial steps to explore the dependencies and knock-on effects related to staff. Regarding the bridge strike, proper risk assessment at a regional and national level would be beneficial. As a next step, a similar reliability engineering approach as explained above would help with understating the criticality of staff and assets for a network of networks and would be relevant for further interdependency related research in this topic. Similarly, Regarding the dependencies in the long term (failure of aging infrastructure) the risk of such failures (probability and consequences) and regarding the dependencies related to inspection and monitoring “the reduction of risk of system failure” would be the relevant metric to investigate as an initial step before assessing “network of networks” vulnerability.

Eventually, regarding the quantitative findings it is generally recommended that improving relevant data availability could facilitate a more detailed analysis and therefore, stronger conclusions. Furthermore, data related to other power stations need to be collected and analysed to interpret a wider range of dependencies at a larger geographical scale. The more specific recommendation considering gaps and limitations are already provided in section 4.8 where the analysed data and results are summarised and discussed.

The next chapter evaluates a different and more local and technical (engineering) level dependency scenario between railways and the urban water distribution system due to a flooding event.

Chapter 5 Evaluation of a dependency- related disruption: the scenario of track flooding caused by a water main burst in urban railways

Chapter 2 presented the existing knowledge in the literature and practice on the topic of infrastructure dependency. Furthermore, in Chapter 4 data analysis techniques have been used to demonstrate the dependency that exists between railways and power sectors in scenarios of commodity supply. However, as previously mentioned in Chapter 2, railways are complex systems consisting of many sub-systems, and interdependencies of sub-systems and other infrastructures vary in nature. This case study focuses on a different dependency scenario, namely the burst induced flooding of an urban railway track and demonstrates how a similar approach is able to improve the understanding of these infrastructure interdependencies. This chapter aims at evaluating the dependency that exists between railways and the urban water distribution system in the scenario of track flooding caused by a water main burst. In order to meet the aim of this chapter the following objectives have been addressed:

- to recognise the dependency that exists between an urban railway and urban water systems (Section 5.1),
- to carry out a critical literature review of the knowledge concerning urban railway flooding and water main bursts (Section 5.2),
- to propose a framework that investigates the dependency between the urban water system and railway operation (Section 5.3), and
- to apply the proposed framework to a case study of the Thameslink railway and Thames Water assets in London (Section 5.4).

5.1 Background

Geographic dependency occurs when elements of multiple infrastructures are spatially proximate and unexpected events create correlated changes in the proximate infrastructures simultaneously. In a normal operating condition, these infrastructures are not necessarily physically connected and the state of one infrastructure does not influence the state of the other (Rinaldi et al., 2001). Disturbances in one infrastructure can traverse to other (geographically dependent) infrastructures and possibly can return to the infrastructure where the disturbances originated. Cascade failures can illuminate interdependencies in infrastructures and are considered as a vulnerability to the normal operation of systems (Johansson and Hassel, 2010). According to the Royal Academy of Engineering, (2011), infrastructure interdependencies need to be understood and managed properly to protect systems against cascade failures and to improve resilience and adaptation of future changes. Cascade failures may represent a significant threat to infrastructures especially because the extent and complexity of events that may lead to a disruption are not well known.

A prime example of such dependency at operation level for railways is the scenario of track flooding in a city. A burst in a trunk water main adjacent to a railway track can cause flooding that disturbs the operation of both of the technical infrastructures (the railway as a transport system and the water supply system). In January 2015, water from a burst water main stayed on the track around Farringdon (Thameslink) and led to track flooding, which stopped the operation of trains for 2 days (Evening Standard, 2015). London Underground experienced a similar incident in June 2012 when water from a burst water main went into the Central Line’s tunnel and stopped the line for 2 days (BBC, 2012). The consequences of similar incidents can vary from a few minutes to days of train delays, interruption to water supplies, and financial and social losses for the railway and the water supply company.

In addition to pluvial and fluvial flooding in urban areas, two other types of flood hazard sources have been recognised: burst water mains and direct connections (sewers) (TfL, 2017). The limited infiltration and drainage capacity in urban areas and the highly complex interaction of infrastructure systems (utilities, water supply, transport, etc.) together with the population density may represent a genuine challenge. Floods pose a considerable risk to the assets and the operation of technical infrastructures. Railway assets and especially track and trackside assets are liable to be disrupted by undrained water (flooding) in flood-prone areas such as at the foot of cuttings and natural slopes, over and under bridges and inside tunnels. In a recent report issued by the Railway Safety and Standards Board (RSSB, 2015) it has been clearly stated that any flood water can harm railway rolling stock and infrastructures (track) and affect the operation of trains.

The behaviour of the flood may vary depending on the source(s) of flooding and the physical attributes of the flooded premise(s) (e.g. railway track, road, underground tunnels and house basements) in urban areas. Considering the nature of dependency between the two infrastructures, it is also important to note the role of drainage and sewers. In some cities (e.g. London) railway drainage is directly connected to urban sewers which are an element of the urban water system (owned and managed by the same water company). This means that any water that enters the premises of railways (e.g. tracks) and absorbed by railway drainage ends up in sewers where inadequate capacity and/or functioning may already be a challenge or will become one in an indefinite future. This provides a good example of cascades and feedback loops between interdependent infrastructures where causal loop analysis/diagram capturing the causal influence among different variables could potentially provide a useful modelling approach (for more information refer to Setola and Theocharidou, 2016).

Furthermore, while an urban railway system transports passenger according to a timetable, an urban water system is responsible for both a consistent water supply to the public and wastewater management. Therefore, although flooding is considered as a risk for both geographically proximate systems, its impact on the operation of a railway system would be more direct. This is because the water supply system may still be able to provide water to customers (and hence meet the system's purpose) while the flooded railway system cannot operate normally before the necessary handling has been implemented. It is important to acknowledge that in some cases, the responses of companies to disruptions may deviate from the actual contingency plan due to conflicts of interest. For instance, to stop the water running out of the burst, the water supply (for customers) needs to be stopped within the premises of the incident and this may be considered a higher risk for the water company than flooding a proximate infrastructure (in this case railways). However, from the viewpoint of a railway infrastructure manager, the leakage must stop as quickly as possible so that their customers (train operating companies) may run the services. Therefore, from a modelling perspective, parameters such as the time of flow running in the premises of the track must be adjusted accordingly based on the information experts provide. Such information/data together with many other relevant modelling input data concerning the phenomenon cannot be found from other sources and need to be collected only from practitioners. Hence, it is important to note that there is a lack of information about the general dependency scenario and challenges in collecting data. Also, because the scenario has never been considered as a cross-sectoral risk which may impact the operation of two urban infrastructure systems, literature reveals the lack of a proper tool or framework that can demonstrate, evaluate and quantify it.

Note that this study aimed at understanding neither the underlying factors of trunk main failure nor its likelihood and risk. Rather it aimed at understanding the impacts or consequences such bursts have on railway infrastructure and operation. As the term “interdependency” indicates, linkages and impacts between infrastructures may be bidirectional (Otto et al., 2016). Therefore, the scenarios of the disruption of a water supply system caused by railway operation and maintenance also require attention. Examples of this include the deterioration and damage of water assets due to maintenance activities such as track tamping or the current from track circuits. However, this study focuses only on the direct impacts of main burst induced flooding on railways.

5.2 Literature Review

Reviewing the literature concerning the event of track flooding caused by a water main burst in a city represents a unique combination of challenges. First, water main bursts and direct connections have never been considered as a significant source of flooding in academic literature, which has only ever focused on pluvial and fluvial/tidal flooding using relevant hydrological and hydraulic calculations. This is because burst water mains are very difficult to predict and generally occur randomly, most likely because of infrastructure failure.

Water main burst/failure receives some attention in the academic literature mostly when the ability to forecast the burst behaviour is necessary for pro-active planning and investment. It is suggested that the behaviour of water main bursts is controlled by many factors. For example, a significant proportion of water main networks in the UK are Victorian cast-iron pipes of 100 years old and generally, it is said that aging mains are more likely to leak and burst/fail. However, age on its own is not a proper indicator of water main bursts. Generally, water mains are exposed to different physical, chemical and loading factors in their operating environment and hence each of these could influence the burst (Boxall et al., 2007). The main factors which contribute to water main bursts can be classified as follows:

- Pipe geometry (e.g. diameter and length), material type, pipe-soil interaction, manufacturing flaws and quality of installation
- Internal loads due to operational and transient pressure and external loads due to soil overburden, traffic loads, frost loads and third-party interface (e.g. maintenance or construction activities)
- Material deterioration due largely to external and internal chemical factors that lead to corrosion (Makar et al., 2001 and Rajeev et al., 2014)

Overall, age and burst history of any main/pipe are essential factors to be considered by practitioners regarding the likelihood of a burst (Boxall et al., 2007). Furthermore, regarding the mechanisms of mains failure: “a pipe may fail when the generated stress exceeds the nominal material strength; when the stress intensity generated at a critical defect” (for instance, because of pitting corrosion) exceeds the material toughness; or possibly as a combination of both mechanisms (Rajeev et al., 2014). This is regardless of the source of loading triggered by any of the above-mentioned factors. Consequently, “pipelines reach failure states when the pipe at a location loses its structural capacity due to corrosion, aging or damage” (Rajeev et al., 2014). Note that, further details regarding the failure modes and the actual way mains fails which significantly depends on the material of the pipes (e.g. cast-iron) stays beyond the scope of this research. Such investigations include the explanation of factors (e.g. corrosion or internal loading) which play a major role in causing each failure mode. For example, Makar et al. (2001) investigated six different failure modes for cast-iron pipes namely; blowout holes, circumferential cracking, longitudinal splitting, bell splitting, bell shearing and spiral cracking. The study stated that for trunk mains (or large-diameter pipes) the most common failure modes are longitudinal splitting and bell shearing. Longitudinal splitting failure mode is more likely to occur because of internal water pressure, to crushing forces acting on the pipe or possibly to compressive forces acting along the pipe (see Figure 95). Any of these loadings could create a longitudinal crack and once the crack has initiated, it may travel the length of the pipe. Large diameter cast iron pipes also fail by having a section of the bell shear off (as shown in Figure 95), known as bell shearing. A possible cause of this failure mode is compressive forces pushing the spigot of a pipe into the bell of the next pipe in the pipeline. However, it is more likely that bending forces are the actual cause of this type of failure. Simple compressive loading tends to result in a crack that spreads down the length of the pipe, but a bending force would produce this type of shearing. Corrosion pitting failure mode which is a localized form of corrosion by which holes are produced in the pipe are also common on big pipes/mains. Pitting is more difficult to detect than uniform corrosion damage (Makar et al., 2001).

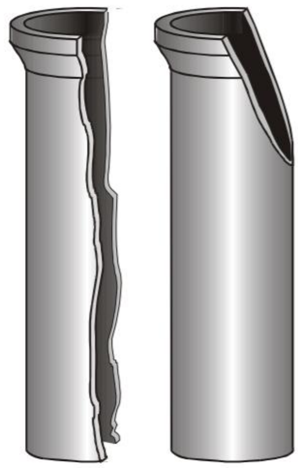


Figure 95 Failure Modes of large diameter cast-iron pipes (source: Makar et al., 2001) The left pipe indicates the longitudinal splitting failure and the right pipe indicates bell shearing failure

Considering the existing academic studies, although burst water mains in general have been investigated before (e.g. Boxall et al., 2007, Cooper et al., 2000, Friedl et al., 2012, Jesson et al., 2017, Srirangarajan et al., 2010, Srirangarajan et al., 2013), the consequences of flooding caused by a burst for a railway or any other infrastructure have been largely ignored in the academic literature. Collaborative research is currently being implemented between Thames Water and the University of Surrey to investigate the causal factors of trunk mains failure, corrosion and deterioration rates, but studying the impact of a burst remains outside its scope (Cuttill, 2017). The literature has focused entirely on the causes and risks of bursts and investigating failure modes, methods of detecting and locating burst events and studying hydraulic driven consequences of bursts. There is also research within the scope of infrastructure dependency and vulnerability which has considered the failure modes of a water distribution network as an urban system (Shuang et al., 2014 and Winkler et al., 2011). Some of these studies focused on the methods for the evaluation of the vulnerability of the water distribution and the consequences of the failure due to a variety of reasons (e.g. a power cut) but not particularly bursts. Hence, although their methodology may be useful at a regional/national scale to understand the systems' vulnerabilities, they do not consider the scenario of bursts and flooding.

London Underground (LU) developed a GIS-based flood risk prediction model within the London Underground Comprehensive Review of Flood Risks (LUCRFR) to include all sources of urban flooding (including direct connections/sewers and mains). The risk analysis was commissioned in 2014, two years after London Underground tracks were flooded by two million litres of water when a trunk main burst. The study found that of all flood sources (namely: fluvial, pluvial, water main burst and direct connections), water main bursts contribute to the highest flood risk for TfL assets (TfL, 2017). The tool focuses only on TfL's assets and excludes other urban railways within the London area (e.g. Network Rail and HS1).

On the other hand, much of the academic railway track flooding research in the past ignored the impact of flooding on the operation of the railway system and mainly focused on the effect and damages flooding causes on the infrastructures of the railways, using empirical and numerical techniques (Benn, 2013, Kellermann et al., 2015, Kellermann et al., 2016 and Moran et al., 2010) to estimate flood losses mostly relating to direct structural and financial damages. Climate change related studies have recognised the impacts of pluvial and fluvial flooding on railways and evaluated these impacts usually in terms of cost and passenger delays (Baker et al., 2010, Arkell and Darch, 2006 and RSSB, 2015).

Full-scale experiments have been used to simulate the geotechnical behaviour of a flooded track, usually relating to the engineering behaviour of the track (e.g. load bearing or drainage design factors) regardless of its impact on running trains or overall services (Hasnayn et al., 2015, Ghataora and Rushton, 2012, Heyns, 2000). RSSB (Rail Safety and Standards Board) in 2015 reviewed the physical phenomena involved in trains running through flood water and found that the UK Rule Book limit which sets out standard procedures for the operation of trains through flood water is appropriate. These procedures are:

1. “If the water depth is above sleeper level, but below the bottom of the railhead, then trains can proceed at line speed.
2. If the water depth is above the bottom of the railhead, but below the top of the railhead, trains may proceed at 5 mph.
3. If the water depth is above the top of the railhead, trains may only proceed if given express permission to do so by operations” (RSSB, 2015).

The actual procedures for operating trains indicate how flood water in reality can be linked to railway services and this may provide useful information for studying the dependency between the two infrastructure systems.

Because the dependency scenario includes the problem of flooding in a city, it would be appropriate to review urban flooding literature and its usefulness in investigating the scenario. 1D and 2D urban flooding modelling techniques are usually used to model fluvial and pluvial flooding scenarios in a city and to understand the complex interaction of flows such as the ones between rainfall and surface flooding as well as surface runoff and underground pipe systems (Mark et al., 2004, Seyoum et al., 2011, Leandro et al., 2009, Hunter et al., 2008, Gallegos et al., 2009). Further input such as land elevation data is required to properly investigate urban pluvial/fluvial flooding. The challenge in the field of urban flooding research is to find the optimum generalised modelling solution to include all the factors involved in complicated flooding phenomena. These tools usually include inputs and calculations which may be unnecessary or irrelevant to consider for a railway track flooding caused by a localised and continuous discharge out of a trunk main. The nature of a burst water mains flooding scenario appears to be different from pluvial/fluvial flooding. For example, because track elevation may vary considerably longitudinally (as track gradient) but not in a traverse direction, any 2D or 3D representation of the terrain/urban surface would be unnecessary. Further details including accurate details of urban surfaces (basements, roads and buildings as well as undeveloped urban land), the interaction of flash floods and waves and surge, large scale flooding (town-wide and river catchment wide), and complicated drainage systems are irrelevant details to the scenario scope. Hence the complicated, time consuming urban flooding models have not been used in this study for the purpose of flood modelling for this specific scenario. However, according to the author's knowledge, there is no available 1D nor 2D modelling tool for railway track flooding. This study has developed a framework to physically model the specific urban flooding dependency scenario and applied it to a case study.

5.3 Framework

This section presents a framework to investigate the dependency between an urban water distribution/sewer system and railway operation. Previous sections attempted to understand the scenario and the dependency under consideration and review the existing knowledge so that a suitable methodology could then be developed. This study used the knowledge of experts (within both railway and water sectors) to envision the reality of the scenario of track flooding caused by a water main burst and its importance for infrastructure managers. The experts provided data and details which were not available publicly (e.g. approximate duration of flooding/burst discharge and flow pressure in the water mains). The flooding of the track depends on many parameters such as ballast porosity, distance from the trunk main, drainage blockage, number of local drainages, time of the flooding, the discharge of the burst etc. All of these have been collected from experts and later were considered in developing a generic model to simulate the flooding scenario. This section explains the framework of engaging with stakeholders to collect the relevant knowledge and later describes how a generic model has been developed to simulate the dependency scenario.

5.3.1 Interviews, meetings and workshop

Similar to the study of interdependencies between ports, railways and power sector (explained in Chapter 4) this part of the research used engagement with stakeholders/experts as a powerful tool to understand a poorly known dependency. Thus, this section explains how the interviews and workshops were set up and used to collect information, knowledge and data.

5.3.1.1 Interviews and meetings

This case study was initiated by several conversations with railway stakeholders which formed after the first case study regarding rail-power linkages (see Chapter 4). As previously explained, the interviews for previous case studies helped identify the stakeholders, including railway experts and their concerns, while the workshop facilitated understanding of poorly known existing dependencies (mostly in form of cross-sectoral risks). One outcome of engagement with railway experts was that they expressed their concerns regarding vulnerabilities in the long term. It has been clearly stated that although some incidents are of low probability (e.g. landslips and ground water movement) they can have very severe consequences for the operation of railway systems and hence they are of high concern for railway managers. Network Rail discussed that one of these concerns is the disruption of the mainlines, due to the issues caused by external assets such as gas pipes, water mains and other utilities. This formed the basis of an investigation for another interdependency scenario and another case study which tackles a different engineering problem while targeting the same hypothesis. The argument is that many poorly known dependencies exist for railway systems which need to be studied academically.

After identifying the concerns for practitioners, railway experts suggested that a similar case study approach would be beneficial for this investigation, since the details of the scenario might vary from case to case. Consequently, due to the nature of the problem, experts recommended Thameslink, who provides a great example due to similar incidents in this area in the past – which means both Network Rail and the water company (i.e. Thames Water) have experience interacting with each other because of such cross-sectoral risks. This specific railway remains within the southern part of Midland Main Line which is managed by Network Rail major routes; LNE and EM (i.e. London North Eastern and East Midlands). Hence, relevant experts within this team who are based in York were interviewed regarding the case study. The team of experts included: one asset engineer with a specific expertise in drainage assets; one senior asset engineer with a similar expertise; and the route asset manager who is responsible for the safe operation of all assets within LNE and EM route (which were partly under investigation for this case study). The experts helped in getting a better realisation of the scenario (from the railway's viewpoint) and in gathering a collection of basic knowledge, information and data (such as track layouts, drainage inspection reports and maps).

Additionally, railway stakeholders played a major role in identifying relevant stakeholders at the external (interdependent) infrastructure, which for this case study was the water company. Hence, the next step was to meet and informally interview the water company's relevant stakeholders to collect similar basic knowledge, information and any data (if available). It has been found that overall, Thames Water Utilities Limited used two key teams to manage the roles and responsibilities, namely: the "clean water" team and the "wastewater" team (i.e. sewer). Since the scenario could represent a serious risk which initiates in the trunk mains, firstly the clean water team was identified as the relevant experts to help with the investigation. However, since further evidence collected showed that in this specific case study, the railway drainage connects to the sewer which is managed by the same water company, the scenario was defined as relevant to experts in both departments at Thames Water (i.e. clean water and wastewater). This is particularly significant while investigating the interdependencies for a) a repair/restoration state of operation (see Figure 4) during which the flood water needs to be drained and b) during a failure scenario in which a sewer system actually floods the adjacent railway track. These stakeholders were sent a research brief in advance and were asked to participate in a group meeting with the purpose of brainstorming and providing further information, as well as encouraging them to contribute to the research.

The stakeholders/experts at Thames Water included a risk modelling specialist who has expertise in modelling and analysing risk for clean water network assets, who also had a background in clean water asset planning. A risk asset manager at the wastewater department with a specific interest and speciality in sewer crossing railways also significantly contributed to the research. Additionally, a production planning manager responsible for the performance of assets, people and processes in the company, as well as a water infrastructure manager who manages asset planners and risk and hydraulic modellers, with a special interest in water quality, network and leakage management were also involved. These experts participated in the meeting and a few informal interviews (through emails) during which they highlighted the issues around leakage and bursts in the case study area. They also provided the GIS files (e.g. shape files) which indicate the location and some other properties (e.g. material, size etc.) of all mains in the case study area.

Note that some may argue that in terms of the complexity of interaction and the degree of dependency between a railway system and water main network in the same urban area, London Underground could provide a better example. As previously mentioned, London Underground also experienced burst induced flooding caused by Thames Water's asset failure and since most of the railway's track in central London is located inside tunnels and cuttings, LU assets are vulnerable to risk of flooding in general (The Guardian, 2016). Thus, two experts at London Underground namely head of pump and drainage and a drainage engineer were interviewed. These experts acknowledged the high risk of flooding caused by direct connections (e.g. mains and sewer) and mentioned that since London Underground already started investigating this type of flood risk, the current research in this thesis would be more beneficial for Network Rail instead. However, they agreed to contribute to the research by providing information, knowledge, sharing their experiences and participating in the workshop.

According to the above, the process of engaging with participants during interviews and meetings can be summarised as follows:

1. Recognising the dependency as a major concern (with high consequences) for railway experts
2. Focusing on the railway route which represents a real-world case study and provides a good example for academic research
3. Establishing communication with relevant experts
4. Collecting non-public primary knowledge, information and data for the scenario through railway experts
5. Identifying the external (interdependent) systems (i.e. the water company) and the relevant stakeholders/experts and encouraging them to contribute to the research by explaining the importance of this topic
6. Collecting non-public primary knowledge, information and data for the scenario through water experts

Railway and water experts later participated in a workshop to further contribute to the investigation of this case study. The next section explains the structure of this workshop.

5.3.1.2 The workshop

A workshop was run on January 27, 2017 at University College London, UK. In total, 5 participants attended the workshop from the rail and water sectors, including Network Rail, London Underground and Thames Water as well as two academics from UoB (University of Birmingham) and UCL (University College London). The main reasons for choosing a workshop approach are that 1) some details regarding the scenario (e.g. potential amount of water or direction of the movement of flood water) which would significantly affect the nature of the modelling and simulation were unknown and could not be found from academic or public sources since these details are only known to local engineers/managers, and 2) whereas interviews and meetings helped as initial steps towards understanding the overview of the scenario, a workshop would allow to obtain a consensus of opinions from a group of experts and local engineers. The following sections explain the details of the workshop as a complimentary methodology for the investigation of this case study.

To ensure that holding a workshop helps meet the objectives of this research in an effective way, a structure was adapted including the following steps:

1. Introducing the background and the aim of the research as well as focus and program of the workshop
2. Introducing and explaining the predefined scenarios for the scenario-based exercises
3. Teamwork, group presentations and outcome collection

First, it was necessary to familiarise or remind participants with the overview of the research and the workshop they attended. During a 20-minute presentation, participants were reminded that this case study is part of a bigger academic project focused on the burst-induced flooding of a part of Thameslink in London. The goal of the workshop was clarified as investigating how water/sewer and rail would affect each other in urban areas as well as to develop a communication mechanism between relevant organisations. The participants were also encouraged to collaboratively identify potential risks around interdependencies and risk alleviation measures since such elements could motivate them to communicate more effectively. During The program of the workshop which was run for 5 hours (including breaks and a networking lunch) the details of participants were also introduced (e.g. names and organisations). Later, a summary of the information which was collected from public sources and at the interviews was presented and eventually the support of the interviewees and the workshop participants was acknowledged.

Later, the senior asset engineer (drainage) at London Underground/TfL gave a 20-minute presentation regarding the understanding of TfL about flood risk and the current risk analyses practices. The goal of this presentation was to elaborate on the topic of discussion since this organisation (TfL) already identified the risk of flooding for their assets.

Next, since the workshop focused on the impact of disruptions, two predefined scenarios were introduced to the participants to focus on during two 1-hour exercise sessions. The nature of the scenarios represents the interfaces between water/sewer and rail systems both in the same case study area with slightly different challenges. Additionally, the scenarios have been created considering the information found during the initial investigation phase (by desk study, meetings and interviews) such as the track layout, inspection reports, drainage maps and the location of the mains. It should be noted that a scenario-based approach was chosen for this workshop because first, interviews revealed that experts are more concerned about the vulnerabilities which could result in similar disruptions to the past incidents and could more severely affect the railway operation and adversely affect the water network. Second, since the nature of flooding varies significantly from one case to another (e.g. because of topology, local drainage issues etc.) a more limited yet useful framework could be more beneficial to investigate this type of technical dependency.

Hence, based on the interviews and the previous desk studies, the following scenarios were created for discussion in the workshop:

- Scenario 1: The track between Farringdon station and St Pancras which is 1.6 km long and passes through cuts and tunnels (see Figure 96) is flooded because of an adjacent water main bursting. Drainage, sewer and water main locations are known (provided to participants in form of maps and reports). Several overbridges where a road passes above the railway also exists in the case study area. Both Thameslink and London Underground runs services in the case study area between the two stations.

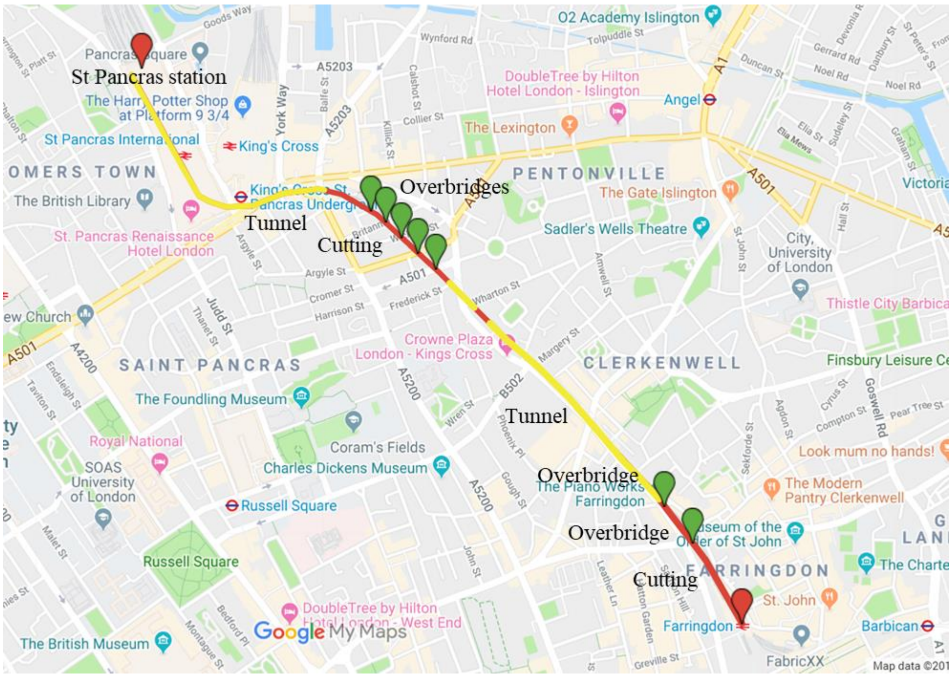


Figure 96 Track extension in the case study area of scenario 1

Note that yellow and red lines indicate tracks passing through tunnels and cuttings respectively. The green icons indicate the location of overbridges where a road passes above the railway. The map was adapted from Google Maps, under Google's policy on reuse and annotation of its maps.

- Scenario 2: The track between Kentish town station and the mouth of Belsize tunnel which is of 0.95 km length and passes through cuts and tunnels is flooded because of heavy rainfall (flash flooding). The railway drainage flooded and/or the connected sewer in the area is overwhelmed. Drainage, sewer and water main locations are known (provided to participants in form of maps and reports). Several overbridges where a road passes above the railway also exists in the case study area. Also, a railway bridge passes above this track which belongs to North London Line (NLL) operated by London Underground (see Figure 97). Thameslink, as well as some freight services, run on the track in the case study area between the two stations.

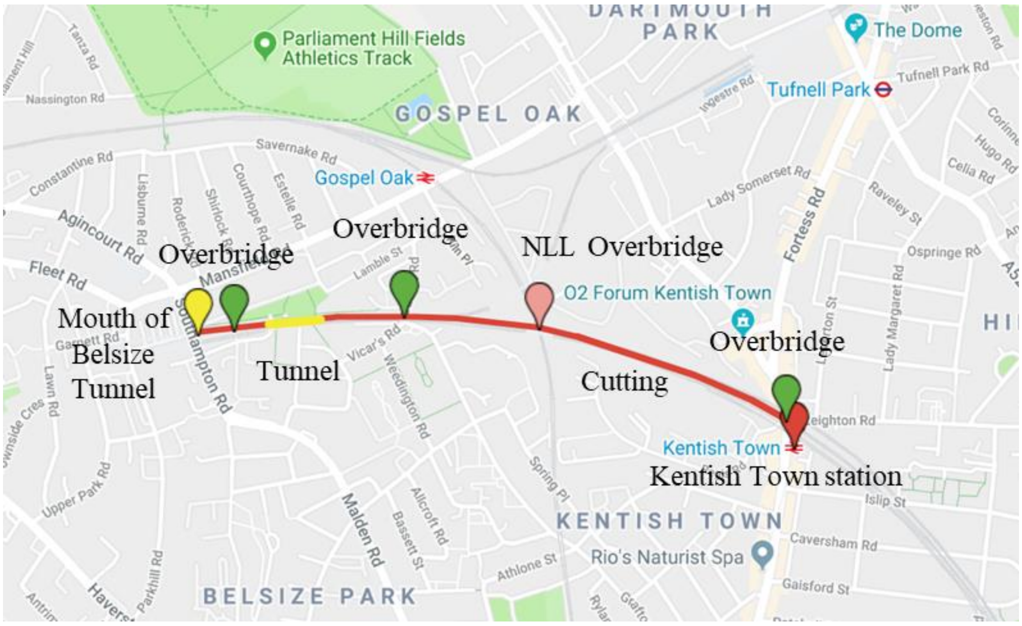


Figure 97 Track extension in the case study area of scenario 2

Note that yellow and red lines indicate tracks passing through tunnels and cuttings respectively. The green icons indicate the location of overbridges where a road passes above the railway. The pink icon shows the location of North London Line railway bridge and the yellow icon shows the location of the mouth of Belsize tunnel where a boundary of this case study area is located. The map was adapted from Google Map, under Google's policy on reuse and annotation of its maps.

Next, for each scenario the participants were provided with printed maps and layouts as well as any available and relevant data and information, and asked to focus on the following elements:

1. Identify potential sources of water/cause of flooding:
    - Potential reasons for flooding in/around railway premises: flash flooding as well as direct connections including sewer flooding and burst water mains or any combination of the above causes
    - Estimating potential amount/volume/flow of water entering the railway premises and the duration of this type of flooding

- What would railway and water companies do at the start of flooding (including their internal procedure)? How would each liaise with external organisations?

2. Find the (potential) movement of water while entering the railway premises:
    - Identifying what would be the potential entrances (e.g. tunnels and lifts)
    - Estimating potential amount/volume/flow (how much of the water would come into the railway premise?)
    - What would reduce or prevent potential water entry?
    - What would water and railway companies do during flooding including their internal procedure? How would each liaise with external organisations?
3. Find how water moves and expands within the railway premises:
    - Identifying what would be the potential routes for water
    - Estimating potential amount/volume/flow of water
    - Identifying the consequence of excess water: if water stays in railway premises in an unexpected manner, what would be effects on railway lineside equipment and railway operations?
    - Identifying the vulnerable assets to this type of flooding (for both railway and water/sewer) and explain their vulnerability
    - Identifying the critical assets for each system and the thresholds of flood
    - What would water and railway companies do (including their internal procedure)? How would each liaise with external organisations?
4. Explain what the action plans would be (responding to the incident):
    - Explaining the response of each company and internal procedures to the incident of flooding: a) before the flooding is obvious (leaks observed) b) when flooding is obvious c) before the flood peak (railway premises flooded) e) after the flood peak
    - Elaborating on the sequence of the actions, predictive duration of each action and the constraints as well as any communication mechanism

All discussions during both scenario-based exercise sessions were recorded by a voice recorder and a video camera/camcorder for further analysis. The outcome of the discussions, including the collected data and information were used to develop the realistic modelling tool presented in the following sections. The data and information were also used in further sections of this chapter (e.g. section 5.6 case study, where the references to these interviews and the workshop are mentioned in the text).

5.3.2 Generic model setup

This section explains the modelling overview and how to specify the problem, input and output, modelling track and water movement as well as the calculation setup.

5.3.2.1 Modelling overview

The flooding of railway tracks by a significant flow from a water main burst has never been investigated in the past, to the best of the author's knowledge. Hence for the benefit of the readers, the problem is first approached from a full-physics perspective in this section.

The water from the burst will move with gravity towards the lowest point of the track. While the water is moving it fills the gaps in the ballast and this reduces the flow rate and thus the speed of the water front. Once the gaps (voids) are fully filled, some of the water is absorbed through the different layers of the sub-ballast and some is drained through the drainage system. The remaining water moves along the track with a speed that is related to the slope of the track, the remaining flow rate after the drainage, dimensions of the track and the ballast roughness. This phenomenon is similar in physics to the dam-break problem. A dam-break problem is the evaluation (through modelling and simulation) of propagation of an uncontrolled release of water because of a dam failure. A dam failure is a collapse or movement of part of a dam, or its foundation in a way that the dam cannot retain water (Wrachien and Mambretti, 2009). Dam failure can occur due to causes such as geological instability, human errors and internal erosion of a dam which is also known as piping (see Figure 98).

Figure 98 A dam failure by piping in Tunbridge dam, Tasmania, Australia (source: Wrachien and Mambretti, 2009)

For a one-dimensional dam-break problem it is acceptable to describe the flow after the breaking of a dam by the shallow water equations which is derived from equations of conservation of mass and conservation of linear momentum (i.e. the Navier–Stokes equations) for an incompressible fluid (Stoker, 1992). In shallow water equations it is assumed that the depth of the water is adequately small compared with some other significant length like the wave length of the water surface. Also, in the first moments after the breaking of a dam, turbulence, viscous effects in the fluid and friction at the bottom can be neglected (Uppsala University, 2002). Similarly, a large burst along a railway track would behave like a one-dimensional dam-break problem. However, for dam-break problems the absorption of water into the ground and drainage are normally neglected. In addition, if the flow rate is significantly large then the shallow water approach is not suitable. It should be noted also, that if the width of the flooded area is significantly large (which is not the case for tracks running through cuttings and tunnels) a two-dimensional approach would be preferred. This includes using the two-dimensional version of Navier-Stokes equation (see Stoker, 1992).

To simulate the track flooding area, the track has been simplified as shown in Figure 99. The model includes all the required parameters that could affect the railway flooding such as ballast porosity, drainage system, slope of the track, distance between local drainage, etc.   In this model, the track was assumed to consist of a layer of porous media representing the ballast, an inclined plate, a source of flood water and a subgrade layer drainage and local drainages (represented as water sinks at different distances along the track).

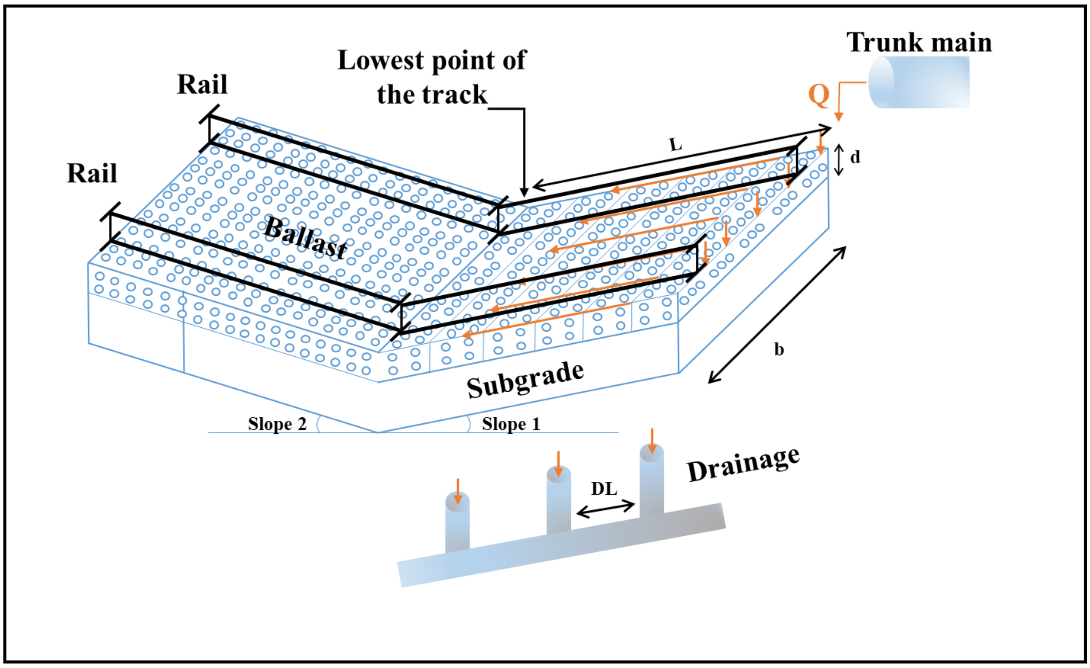


Figure 99 Simplified representation of the railway track in the hydraulic model (NTS)

5.3.2.2 Main inputs and outputs

The main inputs for this modelling are the burst discharge, the track porosity, the local drainage system, the distance between the burst and the lowest point on the track (flooding point) and the slope of the track. The main outputs are the velocity of the flooding water, the depth of the flooding water and the time it takes to flood the track as a function of the different input parameters.

5.3.2.3 Modelling track topologies

The model assumes that the water is distributed uniformly along the width of the track. In addition, it assumes that there is little but continuous drainage through the sub-ballast layer. These are reasonable assumptions as most tracks in urban areas are flat in the lateral direction and the soil/sand formation in subgrade is normally very saturated. This is similar to the condition of London clay. Once the ballast layer is saturated and all the air gaps/voids in ballast are filled with water then the track would no longer be porous, and the water would move in a shallow layer above it. Further the capillary effect and evaporation were ignored in the model as the flow rate and flow velocity are quite large compared to the effect of both capillary effect and evaporation.

5.3.2.4 Modelling water movements

The hydraulic calculation of the flow down the slope was mainly based on the Manning equation (Equation 5.1), which is used for the calculation of flow variables (including height of water) in inclined open channels. The Manning formula includes the slope of the open channel (gradient of the track in this case) as a variable.

$$\frac{Q}{A} = U = \frac{1}{n} R^{2/3} S^{1/2}. \qquad (5.1)$$

Here, A is the cross-sectional area of the open channel (m^2), n is the Gauckler–Manning coefficient, R is the hydraulic radius (m) and S is the slope of the open channel (Schaschke, 2005).

The cross-sectional area, A, is the width of the flooded railway section times the depth of the water in the steady flooding case. The hydraulic radius, R is defined as ($R = \frac{A}{P}$), where P is the wetted perimeter.

The Manning coefficient, *n*, is an important input parameter that determines the resistance of the flow in the flooded railway. This coefficient depends mainly on the bed roughness, *k*. The roughness depends on some characteristic size of the streambed particles and the distribution of the particle sizes (Limerinos, 1970). For conventional open channels, the values of n can be looked up on tables. However, railways are outside the scope of these tables and thus the value of n needs to be determined. The simplest way for determining a suitable value of n is described by Chow (1959) as:

$$\frac{n}{R^{\frac{1}{6}}} = \frac{1}{21.9 \log 12.2 \left(\frac{R}{k}\right)} \qquad (5.2)$$

Normally the roughness, *k*, is taken as the dimeter of the particles in the streambed. However, the size of particle is not uniform and thus Limerinos (1970) suggested the following formula to obtain the Manning coefficient:

$$\frac{n}{R^{\frac{1}{6}}} = \frac{0.0926}{0.76 + 2.0 \log\ (\frac{R}{d_{84}})} \qquad (5.3)$$

Here, d_{84} is the minimum diameter of particles in the streambed based on the 84-percentile size of particles. Individual cumulative frequency-distribution is used to fit curves for the minimum diameters of different samples of 100 particles, then the particle diameter at 84-percenile is taken.

For the current research, the Manning coefficient is calculated using Equation (5.1) in which the roughness for the gravels used in the lab experiment was 8 mm. However, for actual railway track, Equation (5.3) might be used to determine the actual Manning coefficient for a specific piece of track ballast.

The flood flow was assumed to be a steady and uniform flow in an open channel running for several hours, depending on the time it takes to stop the flow. This is a reasonable assumption as trunk mains are large pipes and carry a significant volume of water at high pressure (TWUL, 2017). The information about the duration of burst induced flooding was collected from practitioners in the interviews and the workshop (who had dealt with similar incidents in the past and hence knew the real-world scenario) and inserted into the model as a variable. Moreover, the amount of water discharge from the burst depends only on the area of the orifice and the pressure difference. The pressure difference is assumed to be equal in all trunk mains in the network as a broad assumption. The flow was calculated according to the size of the orifice (Equation 5.4). In reality there is soil, asphalt, etc around the water main pipe and the flow rate, Q, can be modified accordingly. The burst opening was assumed to be circular.

$$Q = C_f A_o \sqrt{\frac{2\Delta P}{\rho}} \qquad (5.4)$$

Here, C_f is the coefficient of discharge, A_o is the area of the orifice (opening), ΔP is pressure drop and ρ is fluid density (Schaschke, 2005)

Because it is very difficult to predict the size of the orifice in the trunk mains, instead of considering an exact value for the flow in the modelling, a reasonable range (e.g. between lowest and highest source flow rate) has been assumed for the discharge from the trunk mains.

Numerical simulation using MATLAB has been carried out to solve Equation 5.1 and Equation 5.4 in order to model the movement of water from the source (burst) onto the railway premises. The track area has been discretized into elements with cells of equal dimensions through which flood water flows in and flows out, assuming every cell first drains the water, then saturates until eventually water forms as a layer on the top of the cell and later moves to the next (shown in Figure 100). The smaller the size of the cell, the better accuracy of the results. However, the number of cells should not be too many in order to reduce the time of the calculations and thus there is an acceptable number of cells after which the change in the results is not significant. This number determined the size of the cell and was calculated by performing a number of simulations with an increasing number of cells until there was no significant change in the results.

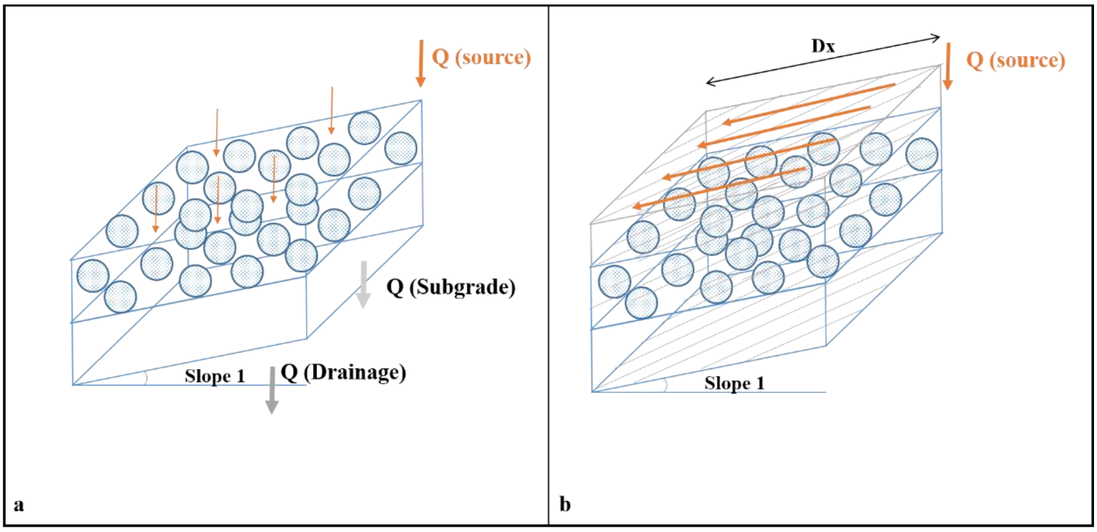


Figure 100 (a) Flow absorption, (b) flow movement on surface of a cell along the track (NTS)

In the model, L, or the distance between the flood source and flood water accumulation point (the lowest point of track) is a parameter and the number of cells along L varies in order to achieve the optimum fidelity and resolution of results. However, the cell size has been assumed as constant and small enough to quantify the outputs accurately.

5.3.2.5 Calculations setup

The point towards which flood water moves and at which it accumulates along the railway track is called "the lowest point". The lowest point of a track is where two gradients meet, one of which is downhill and the other uphill in terms of the direction of flood water movement. This depends on the location of the burst and hence the slopes at the side of the burst (before the lowest point).

The developed model can take into account the different slopes along one piece of track (representation of the reality that railways change gradient) as well as the range of porosity of the ballast layer. It should be noted that in order for the burst induced flooding scenario to happen, the track slope should naturally go downhill in the direction of flow in one or a number of gradient(s) until it changes into an uphill slope at the lowest point of the track (Figure 101). The Matlab code has been developed to find out the different lowest points in the track that are vulnerable of flooding. The code divides the piece of track into different windows and identifies the lowest point in each window.

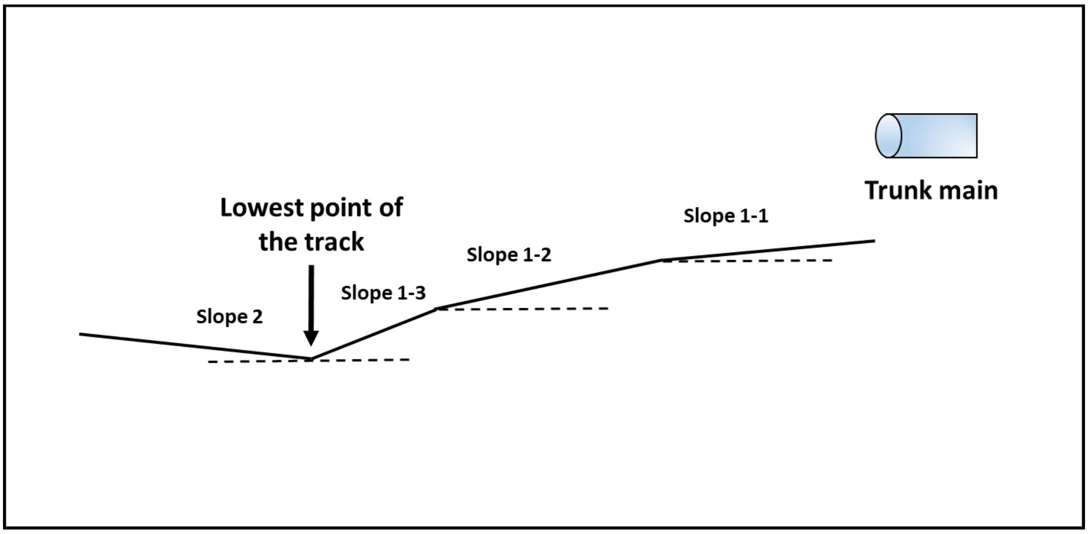


Figure 101 Vertical layout of railway track showing configuration of track gradient in burst-induced flooding scenario (NTS)

Note that in the GB rail network, Engineer's Line Reference (ELR) is usually used, which refers to a location on a railway track. ELRs usually consist of a three-letter route identifier so any place on that route can then be referred to by using a combination of the ELR and the chainage/mileage of the place. Chainage is a term used on railway track layouts and maps to show the running distance along a curved or straight survey line from a fixed start point/origin (Railway Codes, 2019).

To clarify the concept around chainage and gradients of the railways about flooding from a modelling perspective, assume the track layout shown in Figure 102 which starts at the origin 0 m and extends for 1200 m with different gradients. Points A, B and C are potential locations of the burst. If a burst occurs at A and/or B the water moves in the direction of the chainage (from lower chainage to higher chainage) and accumulates at the lowest point of the track. Whereas, if a burst occurs at C, the water moves in the opposite direction of the chainage and accumulates at the lowest point (from chainage 1200m to 1000m). Therefore, note that from a modelling perspective the positive direction of x (along which meshing, and simulation are conducted) should be considered as the direction of water movement which starts from the location of the burst (x=0) towards the lowest point of the track regardless of the chainage. Hence the location of the burst and the location of the lowest point are the boundaries of the numerical simulation. For instance, in case a burst happens at point A, the track between 00m and 1000m is located inside the boundary of the simulation. Whereas this would start from say 300m for point B and 1200m for point C and would end for both cases at the lowest point of the track (chainage 1000m). For this research, the area between the location of the burst and the lowest point of the track is called "the window of the modelling".

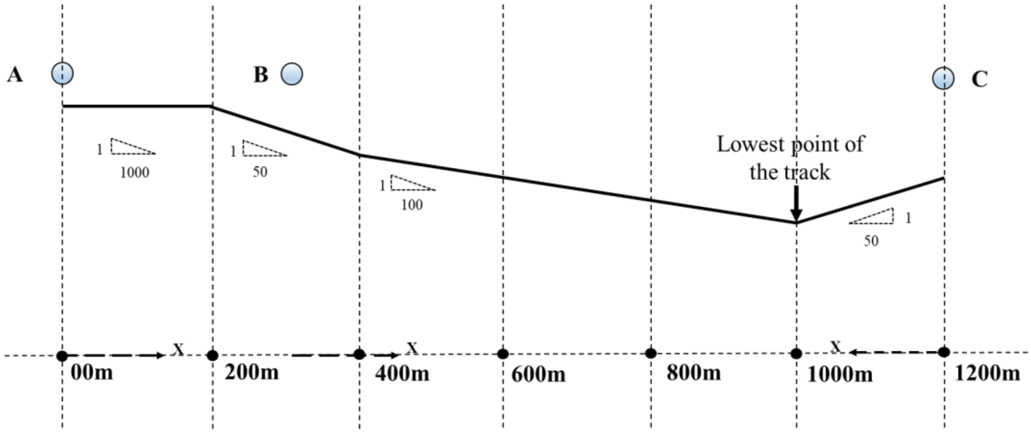


Figure 102 A schematic representation (in a vertical layout) of the track chainage and the direction of flooding for different slope scenarios

From a calculation perspective, to ensure that the domain of the modelling is set properly in the model, the following steps must be followed:

1. Read the track information from a spread sheet file. The spread sheet should include three rows. The total number of chainages is in the first cell of the first row. The second row contains the chainages. The third row includes the track gradient (S). Note the entry in the last cell in the third row is not read as the slope between any two chainages (e.g. between 0 and 10) is indicated in the cell below the first chainage shows (e.g. 0.001 below 0). A typical input data is shown in Table 33.

Table 33 A typical input file for the Matlab code

9								
0	10	40	80	100	120	140	160	180
0.001	0.001	0.002	0.001	-0.002	-0.003	0.002	-0.001	1

2. A Graphical User Interface (GUI) has been developed to read the file as shown in Figure 103.

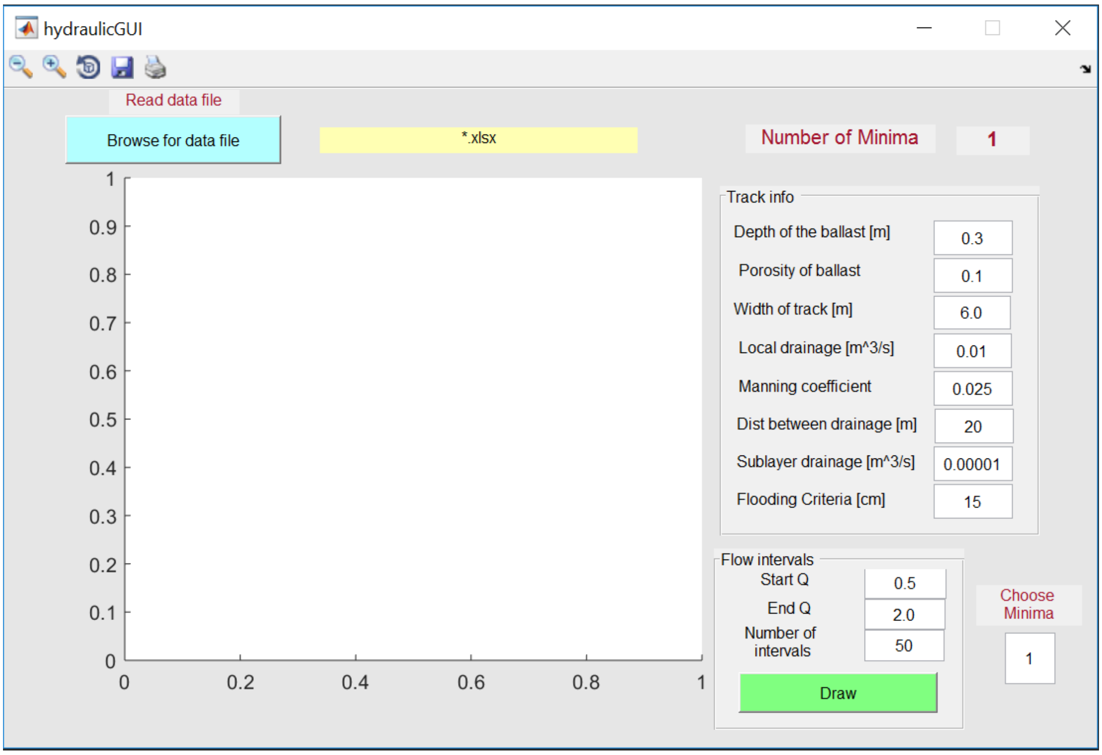


Figure 103 GUI of the Matlab code

In the top left of the GUI a user should browse for the input file. Once the input file is read, a Matlab function has been developed to find out the different minimum points in the track. The number of minima is displayed in the top right of the GUI. Also, a representation of the track is displayed in the drawing area as shown in Figure 104.

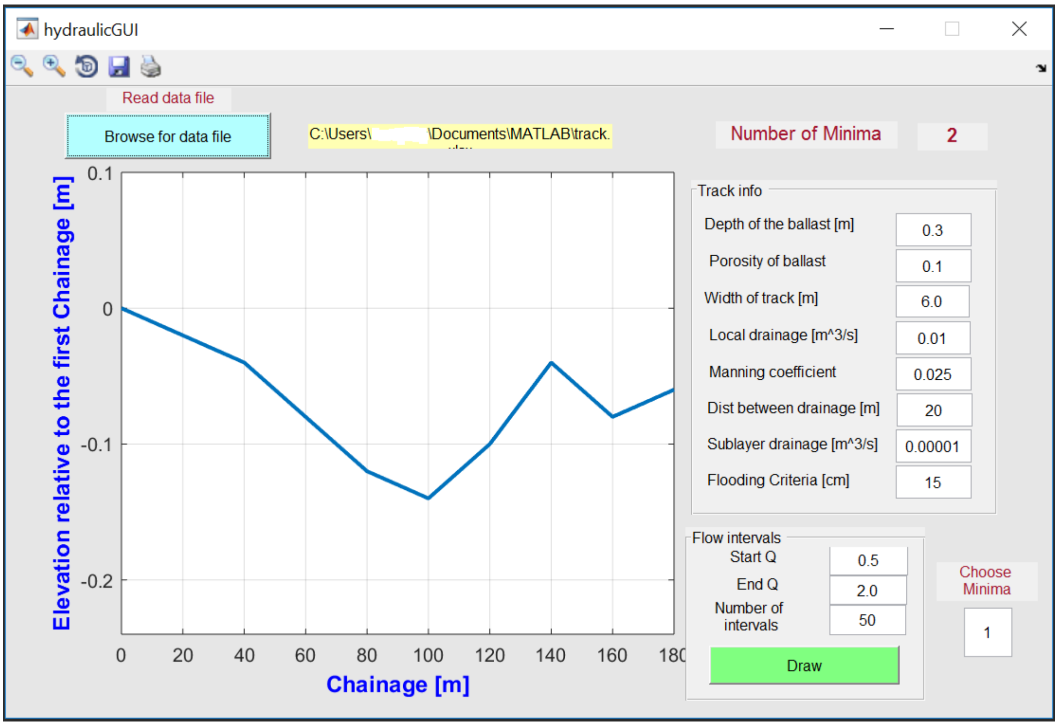


Figure 104 The GUI after reading the input file

3. After reading the input file the user can choose which window to analyse in the bottom right of the GUI and then select the draw button. A typical analysis output is shown in Figure 105.

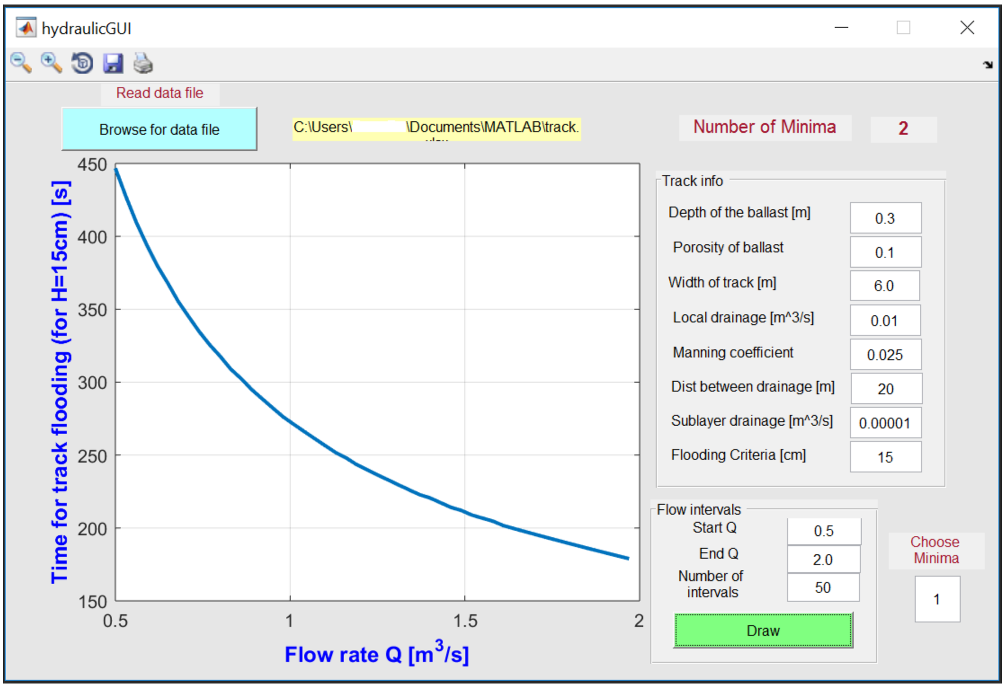


Figure 105 A typical analysis output

Note that all the parameters of the track shown in Figure 103 can be adjusted for different flooding scenarios.

The first part of Appendix E shows how the track chainage is fed into the developed model and the different functions used for this research. Note that for feeding the track chainage into the model, the user of the developed tool should be only able to provide an excel sheet which includes initial parameters (chainage and gradient) as shown in Table 33. These values are available on railway track layouts and maps. This is a reasonable setting because for each burst along a railway track the water accumulation/flooding only occurs at a single point (the lowest point of the track). Realistically for any burst-induced flooding the inflow duration/amount is significantly lower than that of a dam break and hence there is not more than one accumulation point on the track in a one-dimensional problem.

Furthermore, to limit the scope of the work, only the longitudinal track elevation (or track gradient) has been considered in the model. The transverse elevation of the track has been neglected for this study and hence the track is assumed to be of zero cant. One must note that this model is only applicable for tracks with zero cant whereas for larger scales such as mainlines and high-speed railway lines, cant must not be ignored and needs to be considered. This changes the nature of the problem into a two-dimensional flood behaviour analysis which stays outside the scope of this work and needs to be considered as further work (useful academic sources regarding track geometry includes: RSSB, 1998, Esveld, 2001 and Lindahl, 2001).

Furthermore, railway tracks in congested urban areas usually pass through confined spaces, namely cuttings and tunnels, and therefore flood water tends to accumulate (and usually needs to be pumped out) unlike in non-urban areas and unconfined spaces where water has more freedom to move away. Moreover, because only the mains located near the railway track are considered for the modelling, it is assumed that the effect of the transverse elevation would be negligible for the water movement. It is a reasonable assumption because mains located at a greater distance would either have no impact on railways or their impact would be very difficult to predict using one single tool because they also interact with other urban environments (e.g. roads). Local drainage along the track has been assumed to be sinks capable of absorbing a specific volume of water per unit of time either present or absent, representing working and blocked/abandoned drainage in real life.

According to the rule book (RSSB, 2012), the flooding criteria for running trains mainly depend on the rail profile. This model neglected the impact of short circuit and cutting power on running trains. This is because, unlike other flooding scenarios (pluvial and fluvial), the timescale for burst induced flooding is short, but because it is more localised, the flood level may be high. Hence, the realistic impact of this flooding on the operation of railways would be that adjacent tracks would be submerged and hence running trains would be affected. Longer term impacts such as damage to track formation and rolling stocks have not been the focus of this study. Subsequently, the model assumed that if the water depth is above sleeper level but below the bottom of the rail, the maximum height of accumulated water at the lowest point (H_{max}) equals 0. Similarly, the value of H_{max} can be adjusted based on the height of the rail profile for any railway system and the flooding criteria mentioned in the rule book needs to be considered to find the impact on the system (e.g. slowing and stopping trains). This assumption helps in indicating the required time for a particular track to be impacted by a burst-induced flood.

The essential parameters and variables inserted into the model are summarised in Table 34 Note that parameters are those which change from one simulation to another (to conduct parametric studies) whereas variables are those which vary during one simulation as time goes on (from start to end). The constant values are those which due to the assumptions of the problem stay the same both during one simulation and from one simulation to another (e.g. track dimension along a railway line). However, their values might differ for other case studies (e.g. a different railway line).

Table 34 Main parameters and variables in the model

Name in the tool	Type	SI unit	Description and note
Chainage	Parameter	Meter (m)	• The chainage in the input excel file.
Gradient	Parameter	None	• The gradient corresponding to the chainage in the input file.
Q_0 and Q_{end}	Parameter	Cubic meters per second ($m^3 s^{-1}$)	• The lowest and the highest (respectively) source flow rate within a reasonable range depending on the common trunk main size and flow pressure.
Q	Variable	Cubic meters per second ($m^3 s^{-1}$)	• The flow rate at each cell.
d and b	Constant	Meter (m)	• The minimum standard ballast depth (ORR, 2008) and width of a double track. Refer to Figure 99.
$S1$and $S2$	Parameter	None	• The slopes at two sides of the lowest point of the track ($S1$is the slope at the side where burst occurs). Refer to Figure 101. • Note: S1 may be multiple to represent the real-world scenario.

L	Parameter	Meter (m)	• The length of the track calculated as the distance between the location of burst and the lowest point along the track. Refer to Figure 99.
Dx	Parameter	Meter (m)	• Length of each cell in the model (the optimum value assigned to improve fidelity of the results). Refer to Figure 100.
Dt	Parameter	Second (s)	• Time to fill Dx.
$\emptyset$	Parameter	None	• Ratio of void space of the ballast to total volume.
DL	Parameter	Meter (m)	• The distance between local drainages along the track. Refer to Figure 99.
H_{max}	Parameter	Meter (m)	• The criteria for track flooding (the height of the accumulated water at the lowest point of the track).
x	Variable	Meter (m)	• Length along the track, where x=0 is the location of the burst
X_0	Constant	Meter (m)	• The location of the burst where x=0

totalTime	Variable	Second (s)	• Time it takes for the front of the water to move along every cell.
U	Variable	Meter per second (ms^{-1})	• Uniform steady velocity of the water above the ballast in the direction of the flow calculated by Manning equation.
V_f	Variable	Meter per second (ms^{-1})	• Velocity of the water in every cell.
Q_i	Variable	Cubic meters per second (m^3s^{-1})	• Flow rate in every cell.
Q_{sub} and Q_{drain}	Parameter	Cubic meters per second (m^3s^{-1})	• Water flow rate absorbed by the subgrade layer and water flow rate absorbed by the drainage.
h	Variable	Meter (m)	• Height of the water for every cell on top of the track.
V_{void}	Parameter	Cubic meter (m^3)	• Void volume in the cell.

The following steps indicate the main algorithm behind the simulation:

A. Discretize the railway line into several segments of size Dx
B. Assign the parameters such as: 1) the estimated range of the source flow rate (between Q_0 and Q_{end}), 2) track dimensions (d, b and L which are depth and

width of ballast and length of track), track gradients ($S_1$and S_2), $\emptyset$ or the porosity of the ballast, Manning coefficient, subgrade drainage in each 1m length of the track and local drainage capacity for every DL.

C. Set the initial/boundary conditions at zero for the start of the simulation. This means that when simulation initiates, the following parameters equal zero: initial value for the length along the track, initial value for the time it takes for the front of the water to move along every cell, initial uniform steady velocity of the water above the ballast in the direction of water movement, initial front velocity of flow in the direction of water movement, initial value for the water flow rate on the track and initial value for the height of the water above the track.

D. Apply the main formulas to carry out the calculations as follows:

$$h = (\frac{n\,Q}{bs^{0.5}})^{3/5} \qquad (5.5)$$

Equation 5.5 derived from Manning's equation where h is the height of the water on every cell, n is Manning coefficient, Q is the flow rate in every cell, b is the width of the track/cell and s is the gradient of the cell. The uniform steady velocity, U, of the water above every cell in the direction of the flow is calculated from

$$U = \frac{Q}{bh} \qquad (5.6)$$

where Q is the flow rate in every cell, b is the width of the cell and h is the height of the water on every cell. The flow rate at the cell, Q_i, is calculated from:

$$Q_i = Q_{i-1} - Q_{sub} - Q_{drain} \qquad (5.7)$$

Here, Q_{i-1} is the flow rate at the previous cell, Q_{sub} is the water flow rate absorbed by the subgrade layer and Q_{drain} is the water flow rate absorbed by local drainage

$$D_t = \frac{V_{void}}{Q} \qquad (5.8)$$

Equation 5.8 describes the time for the water to fill the cell where V_{void} is the void volume in the cell and Q is the flow rate in the cell. The velocity of the water front, V_f is calculated from

$$V_f = \frac{D_x}{D_t} \tag{5.9}$$

Where D_x is the length of the cell and D_t is the time for the water to fill the cell. The height of the water at the lowest point, h, is calculated based on the Manning equation

$$h = \sqrt{\frac{2V_f}{b(\frac{1}{S_1} + \frac{1}{S_2})}} \tag{5.10}$$

where V_f is the velocity of the front of the flow, b is the width of the track, S_1 is the gradient of the track at the side of the burst and S_2 is the gradient of the track at the other side.

E. Create a number of loops so for every cell you may calculate the following; height of the water above the ballast using Manning equation (Equation 5.5), the uniform steady velocity of the water above the ballast in the direction of the flow using common flow rate equation (Equation 5.6), flow rate at every cell using Equation 5.7, total time it takes for the water to move from the source to a cell using the sum of every Dt and Equation 5.8 and velocity of the front of the flow using Equation 5.9. Plot diagrams as required. Completing this step gives a comprehensive picture of flow (water) movement along the track.
F. Furthermore, in order to find the track flooding rate according to the criteria of the rule book (RSSB, 2012), calculate the flow properties at the lowest point of the track using Equation 5.10. Continue the loops for every Q until the value of h reaches H_{max}. Collect the results and plot figures as required.

Note that the time step in the simulation is calculated based on the void volume and the water flow rate:

$$\Delta t = \frac{volume\ of\ the\ void\ in\ a\ cell}{flow\ rate\ entering\ a\ cell} = \frac{\mathrm{V_{void}}}{Q_i} \tag{5.11}$$

This calculation ensures that the flow would not pass to the next cell at one time step. This formula is also valid for the flooded cells as the assumption of steady state uniform flow condition is applied to them and hence the time is not relevant. Consequently, once the void is filled with water and the amount of drainage (drained flow) is calculated the front velocity can be later calculated.

The summary diagram is shown in Figure 106 which outlines the concept and workflow of the developed model. Furthermore, the MATLAB codes are attached in Appendix E.

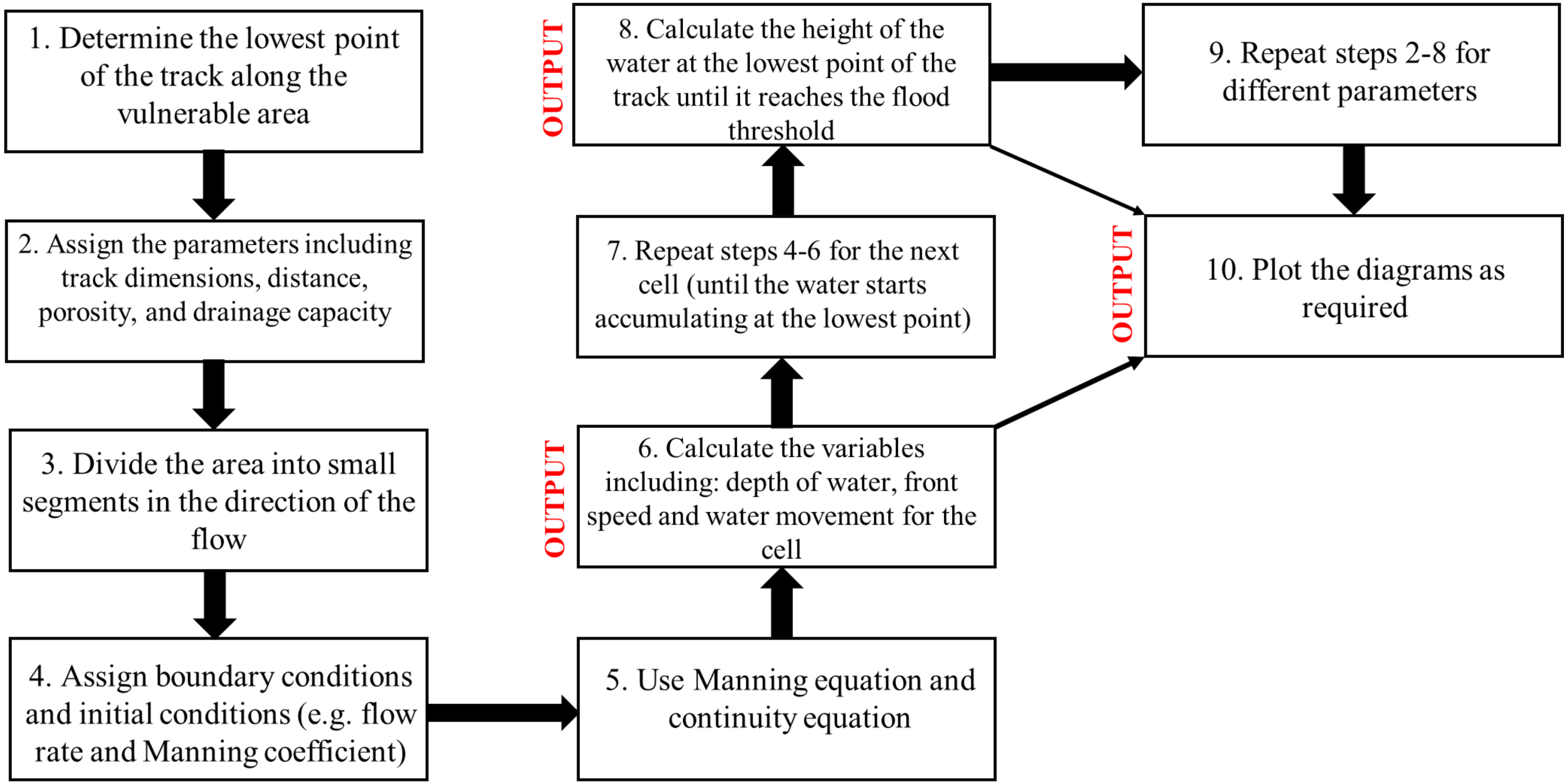


Figure 106 The summary diagram of the developed model

5.3.3 Output of the model

According to the model setup explained in the previous section, the output of the model can be mainly categorised into two parts. First, the model can simulate the water movement and hence calculate the following: the location of the front of the flow in time, the water velocity and flow rate along the flooded track and the depth of the water at the lowest point in time. These figures provide a picture of the water movement along the burst-induced flooded track. Second, for a more practical purpose the model can calculate and demonstrate for every scenario (set of parameters) the time it takes to reach the criteria of flooding. Hence it calculates the time it takes for the water to accumulate at the lowest point (track flooding rate) until it reaches the flooding limit (defined as flooding criteria in the rule book) and indicates the dependency between two systems.

In the next section a case study is carried out using the developed numerical model to investigate a real-world example.

5.4 Validation of the numerical tool

This section explains how the developed numerical tool is validated through mesh sensitivity analysis and a small-scale experiment.

5.4.1 Mesh sensitivity

The mesh sensitivity has been carried out using different cell sizes of 1m, 0.01 m and 0.005 m. The height of the water at the lowest point as a function of time from the different meshes is shown in Figure 107. The results from the 1m cell size are different from those of the smaller cell sizes. However, the results from the 0.01 m cell size are similar to those from the 0.005 m one. Therefore, there is no need to decrease the cell size further. All the results in this chapter are from the 0.005 m cell size. These values of mesh sizes are used for a computational domain similar to the experiment and thus very small mesh size is needed as the total length of the experimental setup is only 2m. For railway track with large amount of water flooding the mesh size could be bigger. However, as this is a 1D code the simulations time would not be affected much if the mesh size is small as the number of cells will remain under 1 million for most of the cases.

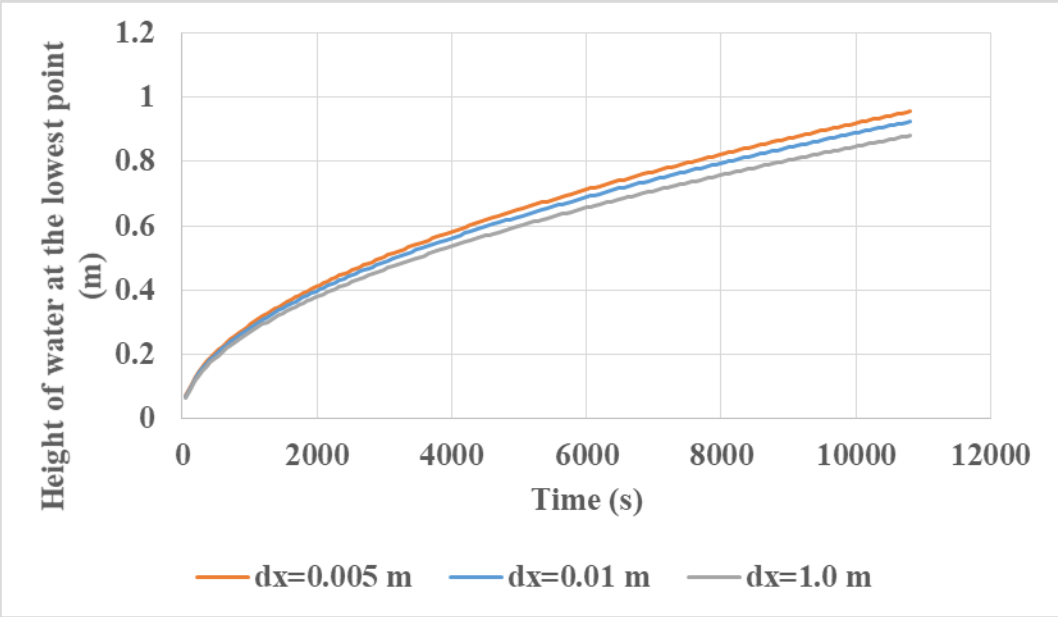


Figure 107 mesh sensitivity analysis

5.4.2 Validation scope

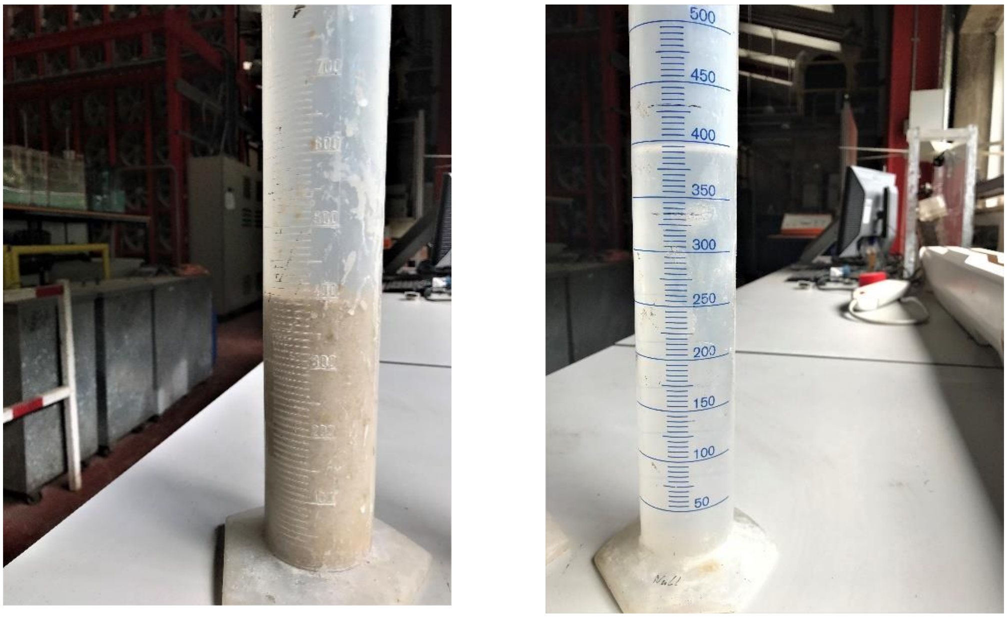
A small-scale experiment has been carried out to validate the numerical modelling tool using a mobile bed model tank at the University of Birmingham in June 2018. The kit could provide a flow up to 0.004 $m^3s^{-1}$and provides self-contained water (by a centrifugal pump) which could evenly flow over the bed of the tank. The main aim of this experiment is to provide data to validate the numerical model.

5.4.3 Experimental method

The area of the experiment (shown in Figure 108 and Figure 109) is supposed to simulate the track bed and hence the area in the numerical simulation. The dimensions of the area are 600mm width and 2000m length. The area is flat simulating zero or very low (e.g. 0.001) gradient. Experiments using two types of granular material, namely sand and gravel, have been carried out to collect the results. The permeability (porosity) of both granular materials was measured before setting up the scaled track bed and running the test. The total volume of a sample of sand and some water was measured by two measuring cylinders (graduated cylinders). Next, the voids between the granular materials were slowly filled with water and the volume of the water was measured (subtracted from the total volume of water present in the cylinder before filling the voids (shown in Figure 110 and Figure 111). A similar process was carried out for the gravel (Figure 112). Dividing the volume of the voids by the total volume of granular materials gave the porosity of each material.

Figure 108 Mobile bed model tank and the flow meter

Figure 109 The area of the experiment in the tank (i.e. the bed is evenly covered with sand)



(A) (B)

Figure 110 (A) The volume of the sand before saturation and (B) the volume of the total water

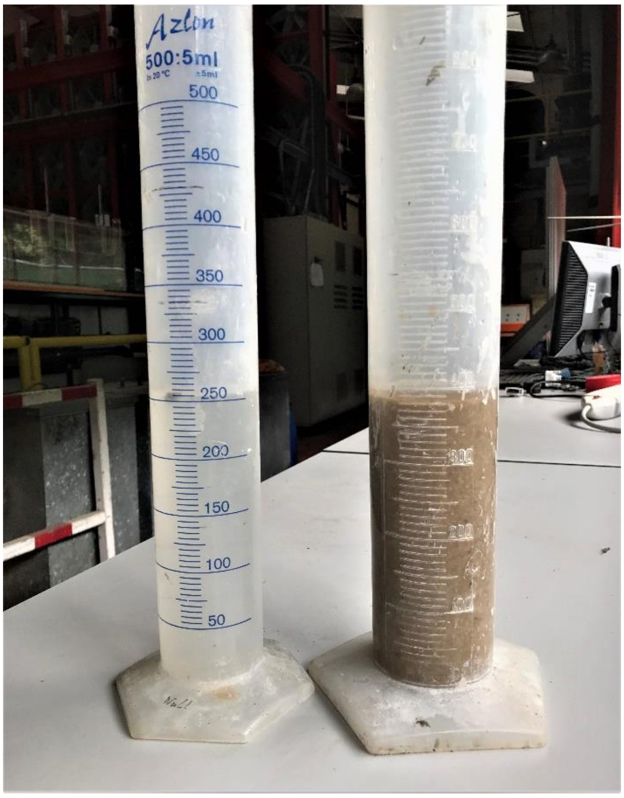


Figure 111 The saturated sand sample on the right and the remaining volume of water in the cylinder after the sand sample is saturated

Figure 112 The saturated gravel (i.e. 175mm of water filled the voids of the total 400mm of granular material)

It is assumed that the gradient is negligible and technically flooding occurs because of water accumulation above the granular bed, since the experiment area is small and there is no infiltration. Table 35 shows the variables and their values in the experiment.

Table 35 Variables in the track flooding experiment

Variable	Value in the experiment	Description
L	Sand: 2m Gravel: 2m	The length of the mobile bed simulating the distance between the burst and the lowest point
b	Sand: 0.6m Gravel: 0.6m	The width of the mobile bed simulating the width of the track
d	Sand: 0.078m Gravel: 0.03m	The depth of granular material on the bed
Q	Sand: 0.00256 m^3s^{-1} Gravel: 0.000671m^3s^{-1}	The steady flow of the water from the tank moving along the bed
Ø	Sand: 0.35 Gravel: 0.44	The porosity of the granular material simulating the ballast porosity
S	Sand: 0.001 Gravel: 0.001	The gradient of the bed simulating a flat gradient
n	Sand: 0.015 Gravel: 0.025	Manning coefficient

Next, the experiment was run to collect the results for both sand and gravel using two different flows of 0.00256 m^3s^{-1}(for sand) and 0.000671m^3s^{-1}(for gravel) (Figure 113 and Figure 114). The steady flow continued until the water reached the end of the granular bed and the height of the flow became constant along the bed (Figure 115 and Figure 116).

Figure 113 Water movement along the sand bed

Figure 114 Water movement along the gravel bed

Figure 115 Water accumulated on top of the sand bed

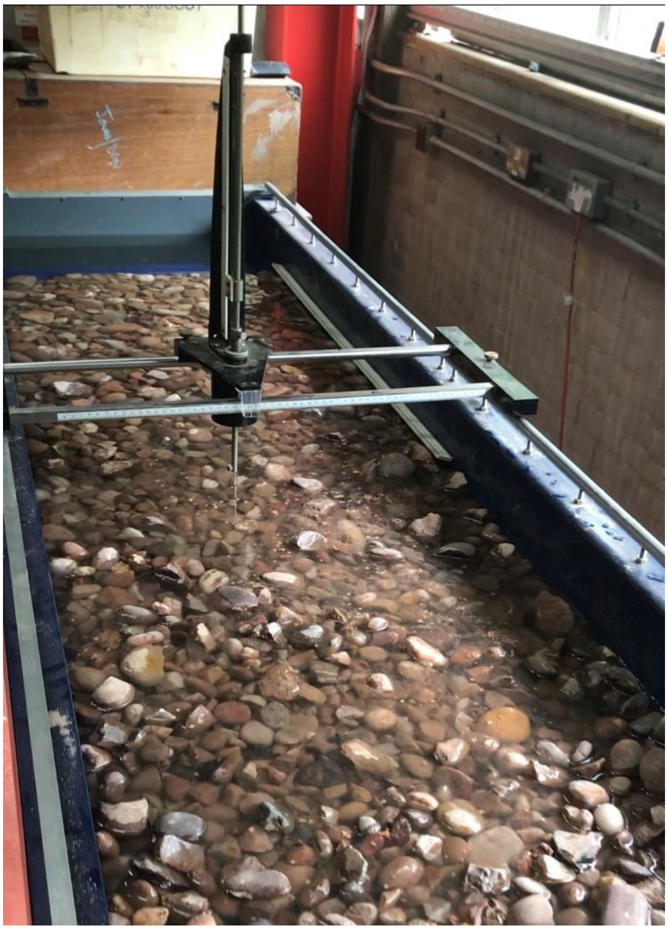


Figure 116 Water accumulated on top of the gravel bed

5.4.4 Results

The main collected output included; the distance of the front of the water from the source ("x" in metres) and the time it takes for the front of the flow to travel the distance ("t" in seconds) as well as the height of the collected water above the granular bed ("h" in metres). Table 36 compares the two sets of output data from the experiment and the numerical model. As the two sets of results closely match, the developed numerical model could be validated and used for simulation of flooding on railway tracks.

Table 36 Comparison of the output from laboratory experiment and developed numerical model

Output	Value from the experiment	Value from the developed numerical model
t (at the end of the track bed at the end of the experiment e.i x=2m)	Sand: 15 s Gravel: 25 s	Sand: 12.80 s Gravel: 23.61 s
h (at the end of the experiment)	Sand: 0.02 m Gravel: 0.01	Sand: 0.02 m Gravel: 0.01 m

5.5 Case study

This section applies the developed model to a section of Thameslink Railway and the southern part of the Midland Main Line in the London area (between Farringdon and Kentish town stations), which its infrastructure is managed by London North Eastern and East Midlands (LNE&EM). In this area, the railway drainage systems are connected to the urban sewer system and railway tracks would be exposed to the risk of burst water mains. The case study helps to test the developed framework presented in the previous chapter. The section of the Thameslink Railway (i.e. infrastructure owned and managed by Network Rail) within the London area (shown in Figure 117) provides a great example to demonstrate the framework's ability to quantify burst-induced track flooding since:

1. This section of the railway is generally flood prone as it passes mostly through cuttings and tunnels in a densely populated part of London, unlike the other sections (e.g. from Kentish Town station to the north) with more vegetated areas.
2. The number and density of trunk mains are higher within the case study area and mains are located within much closer proximity to railways (e.g. right under the railway track in some areas) compared to other urban areas.

Furthermore, past flood records suggest that the case study area is vulnerable to the risk of this type of flooding (e.g. Evening Standard, 2015).

3. Major London railway infrastructure operators, Network Rail and London Underground, as well as the water supply company TWUL agree that it is necessary to develop tools for a better understanding of the shared risk of urban flooding in the area of the case study. TWUL stated that, within the major London railway infrastructure, operators, especially Network Rail, need to improve their knowledge and communication level about the issue of cross sectoral risks.

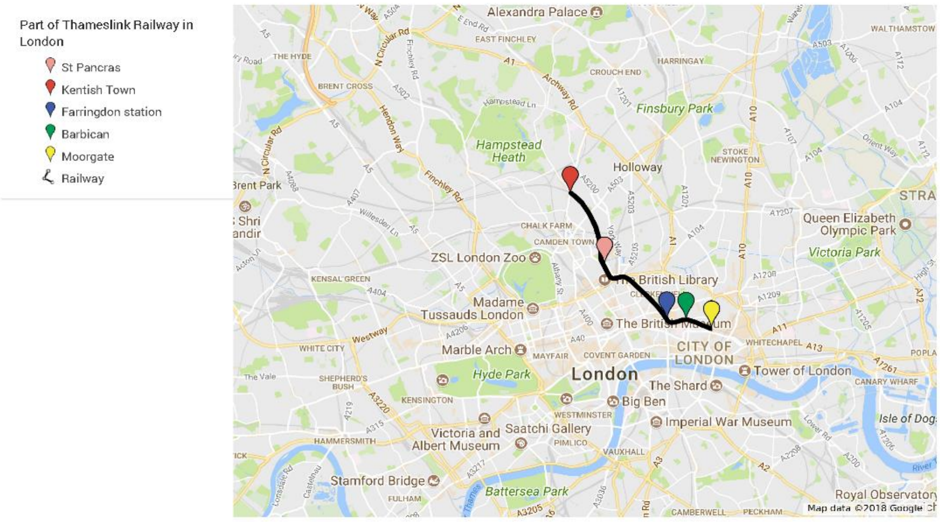


Figure 117 The railway line within the case study area

5.5.1 The case study area

The case study focuses on sections of Thameslink (North of Farringdon) and Midland Main Line within London, where railway track is surrounded by trunk mains with diameters between 18” and 102” and smaller mains of various diameters.

Thames Water Utilities Limited (TWUL) is responsible for supplying clean water and treating wastewater in Greater London and the South of England. TWUL manages approximately 30,000 km of water mains, of which 17,000 km are trunk mains (Cooper at al., 2000). Note that nearly half of the water mains in London are over 100 years old (Thames Water, 2011). Trunk mains are large pipes (usually 18” diameter or larger in

London) which carry a significant volume of water at high pressure (hydraulic head equals 22m). Towards the end of 2016, Thames Water suffered eight separate bursts on their trunk main network (TWUL, 2017). These caused significant damage to infrastructures and businesses, transport disruption, and temporary losses of water supply. After the incidents Thames Water acknowledged that the rate of bursts in larger trunk mains is increasing. Thames Water realized that although the trunk mains failure probability is low, the consequences can be very high for the water company, their customers and other businesses (Cuttill, 2017).

Network Rail is the owner and manager of most of the railway infrastructure in England, Scotland and Wales and is also responsible for maintaining more than 20,000 miles of track including Thameslink railway, a mainline route running through London. Thameslink is a 115-station mainline route running from Bedford, Luton, Peterborough and Cambridge in the north of London via central London to Sutton, Orpington, Sevenoaks, Rainham, Horsham and Brighton in the south of London area. Figure 118 shows the part of the Thameslink route which is around the case study area. The regular Thameslink services which use the tracks between Farringdon station and Kentish town are listed as follows:

- Two train services per hour between Bedford and Brighton (without stopping at Kentish town) (route identity: TL2) in each direction with services from 4:00 until 23:00
- Two train services per hour between Bedford and Gatwick (without stopping at Kentish town) (route identity: TL2) at each direction with services from 4:00 until 23:00
- Two train services per hour Between Luton and Sutton (route identity: TL2) at each direction with services from 4:00 until 23:00
- Two train services per hour Between St Albans and Sutton (route identity: TL3) at each direction with services from 4:00 until 23:00
- Two train services per hour Between West Hampstead Thameslink and Orpington (Kent) (route identity: TL4) at each direction with services from 6:00 until 20:00 (Thameslink Railway, 2019).

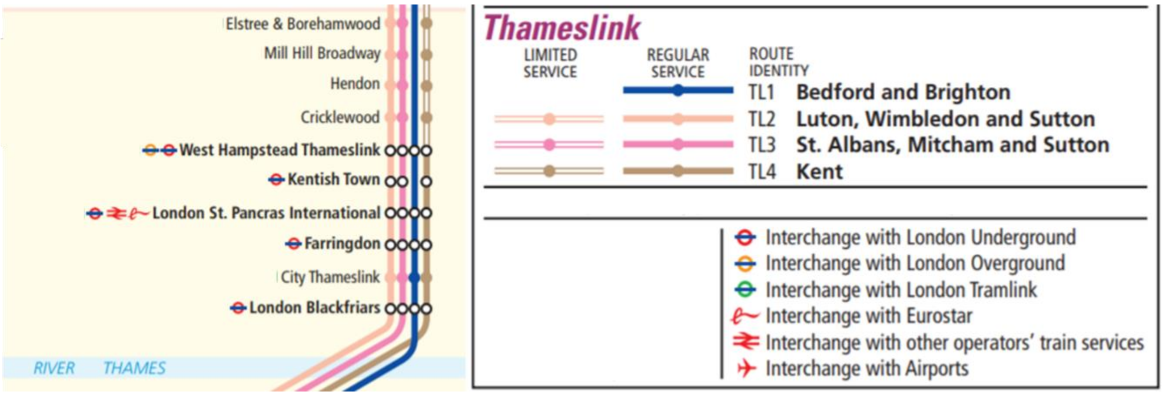


Figure 118 Thameslink route in and near the case study area

The figure is adopted and recreated from Thameslink route map (see Thameslink Railway, 2018 for the complete route map).

This case study argues that because the railway track between Farringdon and Kentish Town is mostly located lower than the surrounding area (i.e. in cuttings and tunnels) it is prone to flooding. Flooding is a risk in urban areas since there is a lack of enough drainage in cities. In London, the railway drainage is directly connected to the public sewer, which represents a unique challenge.

5.5.2 Case study scope

To accurately evaluate the disruption scenario and apply the developed model to the case study, the following data were collected from relevant sources and used as inputs into the developed model:

1. GIS data of trunk water mains (TWUL)
2. Map of railway line (Network Rail)
3. Network Rail drainage, signals and water utilities asset plan (Network Rail)
4. Track layout, features (e.g. bridges and tunnels) and signalling equipment data (Network Rail)
5. Gradient of railway line between Moorgate (in Central London)- Dock Junction North (Kentish Town station in North London) (Network Rail)
6. Policies on the operation of vehicles through floodwaters (RSSB, 2015)

7. General Network Rail standards regarding ballasted track, slab track and drainage (Network Rail, 2011)

In addition to the above, further information (e.g. water pressure in trunk mains, the duration of flooding, etc.) was collected in workshops and interviews with experts, because the values of some parameters were not available publicly or in published documents. An example of such information is the response of companies to the flood event and how a response may affect the flood scenario. For instance, if track flooding occurs, drivers must report any floodwater with the potential to affect the passage of trains to the signaller, who in turn must report it immediately to operations control. As soon as the flooding source is detected and it is reported to the water supply company, a decision needs to be made to stop the water flow by switching off the water supply. Because the size of the trunk mains is large and the water runs under high pressure, the flow may not stop until up to 3-5 hours after switching off the supply. TWUL event response and aftercare includes the operational response to containing the burst and repairing the trunk mains, customer communications and care, as well as stakeholder engagement. Network Rail as the railway infrastructure operator also needs to pump out the undrained water on the track and relay, repair and replace it (if required) as quickly as possible so train operating companies (Thameslink in this case) can run their services again.

5.5.3 General area information

In order to understand the scope of the study some of the collected data are presented in this section as follows:

TWUL’s GIS data provided the location of the trunk mains in the area of case study. Figure 119 and Figure 120 show the location of the trunk mains and smaller mains respectively together with the extension of the railway line in the area.

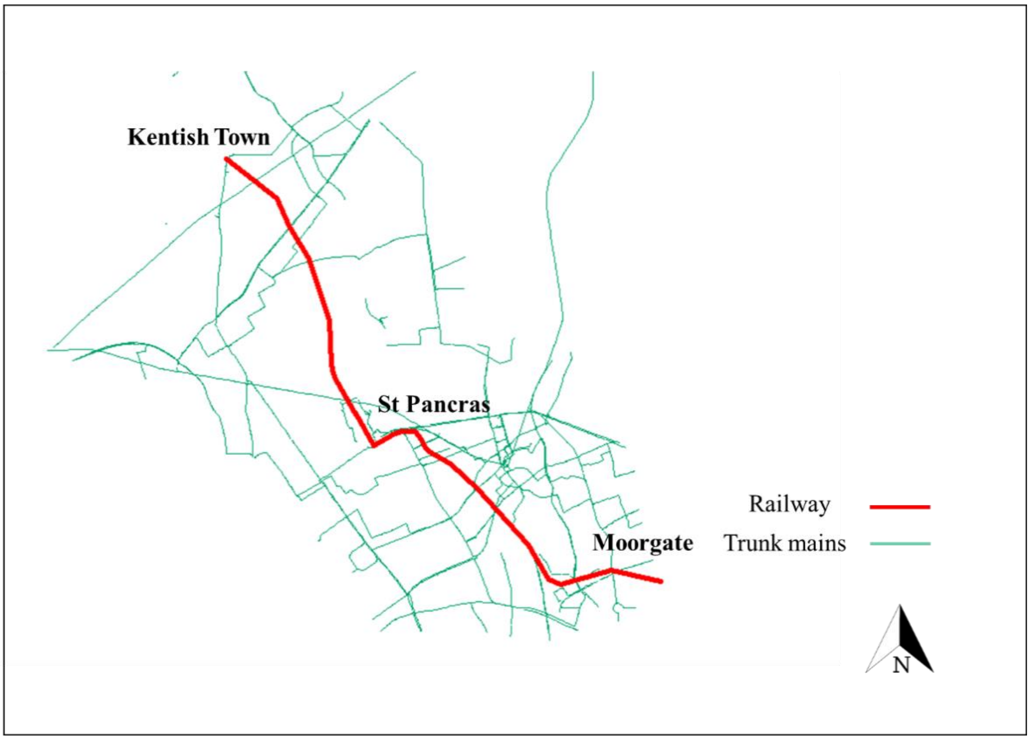


Figure 119 Plan view of case study area showing location of trunk mains and part of the railway line

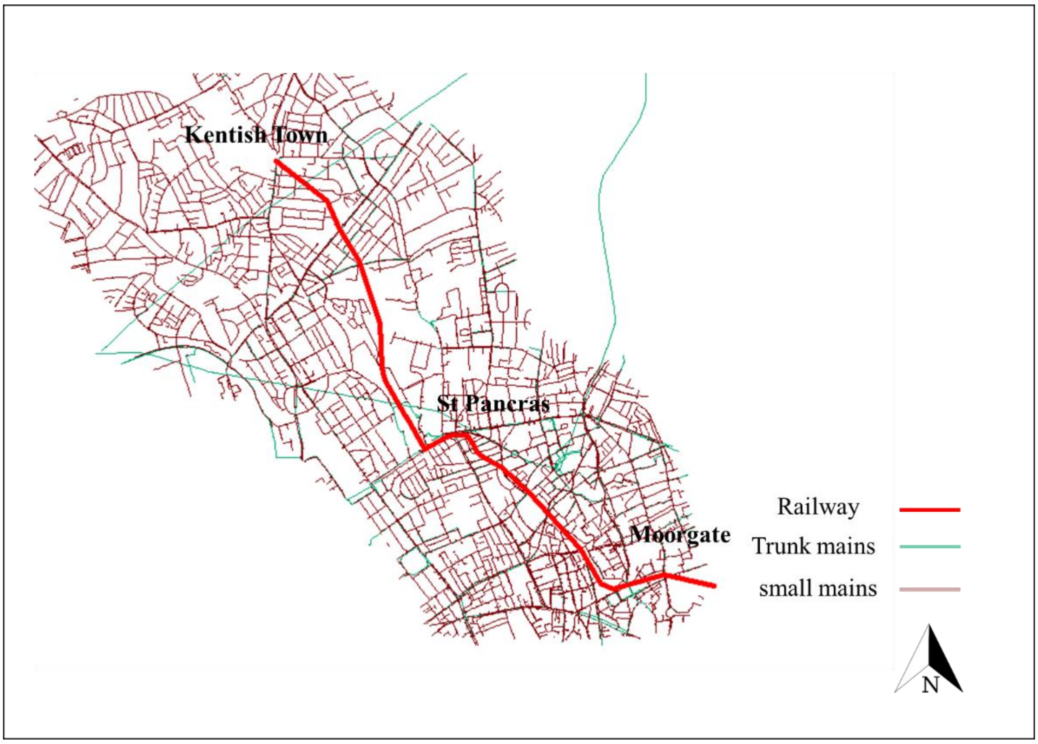


Figure 120 Location of trunk mains and smaller mains in the area of case study

The topographic map of London shows a rise in elevation from Central London towards the North West where the railway line extends (Topographic maps, 2017). Generally, it is reasonable to assume that in a case of flooding the water movement tends to be in the direction of the lower elevation (e.g. towards Moorgate). However, the longitudinal elevation of the track is not constant for the entire line along the case study area. Figure 121 and Figure 122 show different angles of inclination from Moorgate station to Kentish Town station along Thameslink (area of the case study).

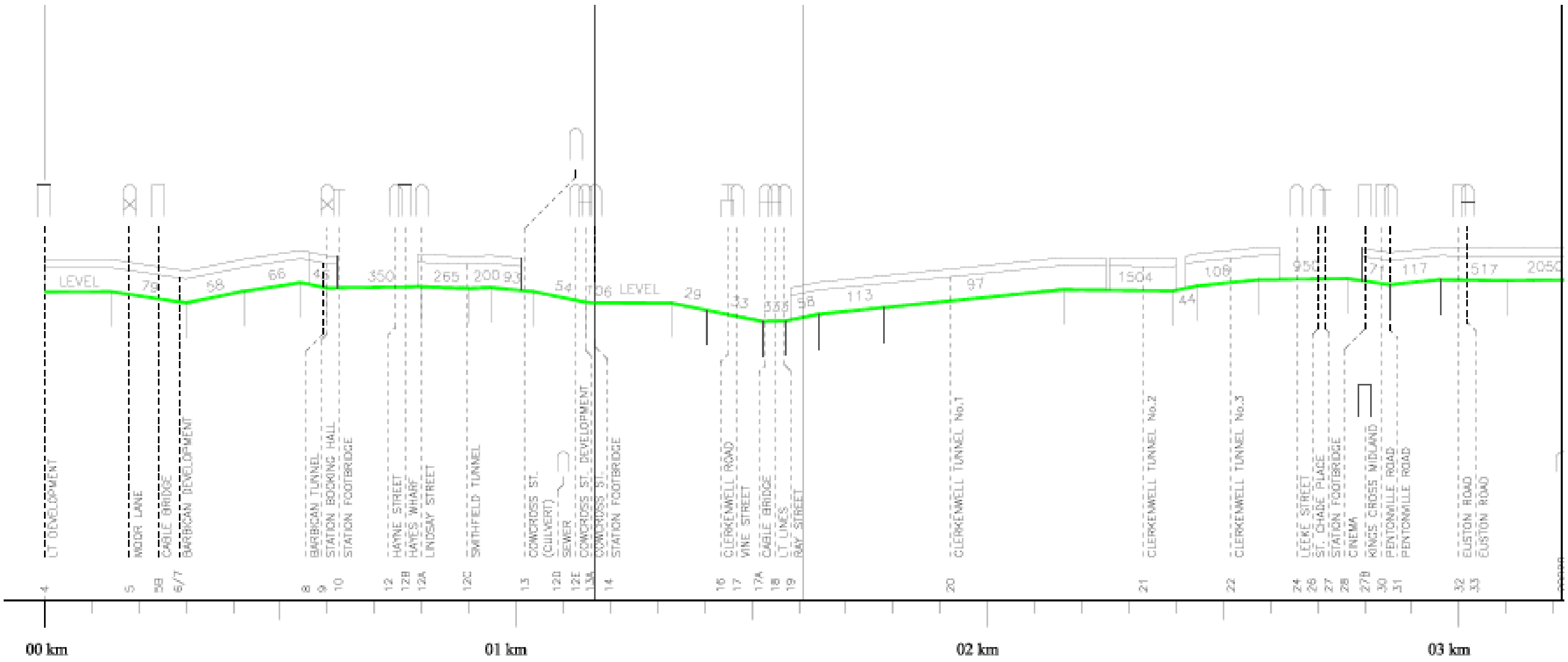


Figure 121 Gradient of the track between Moorgate and Euston in London

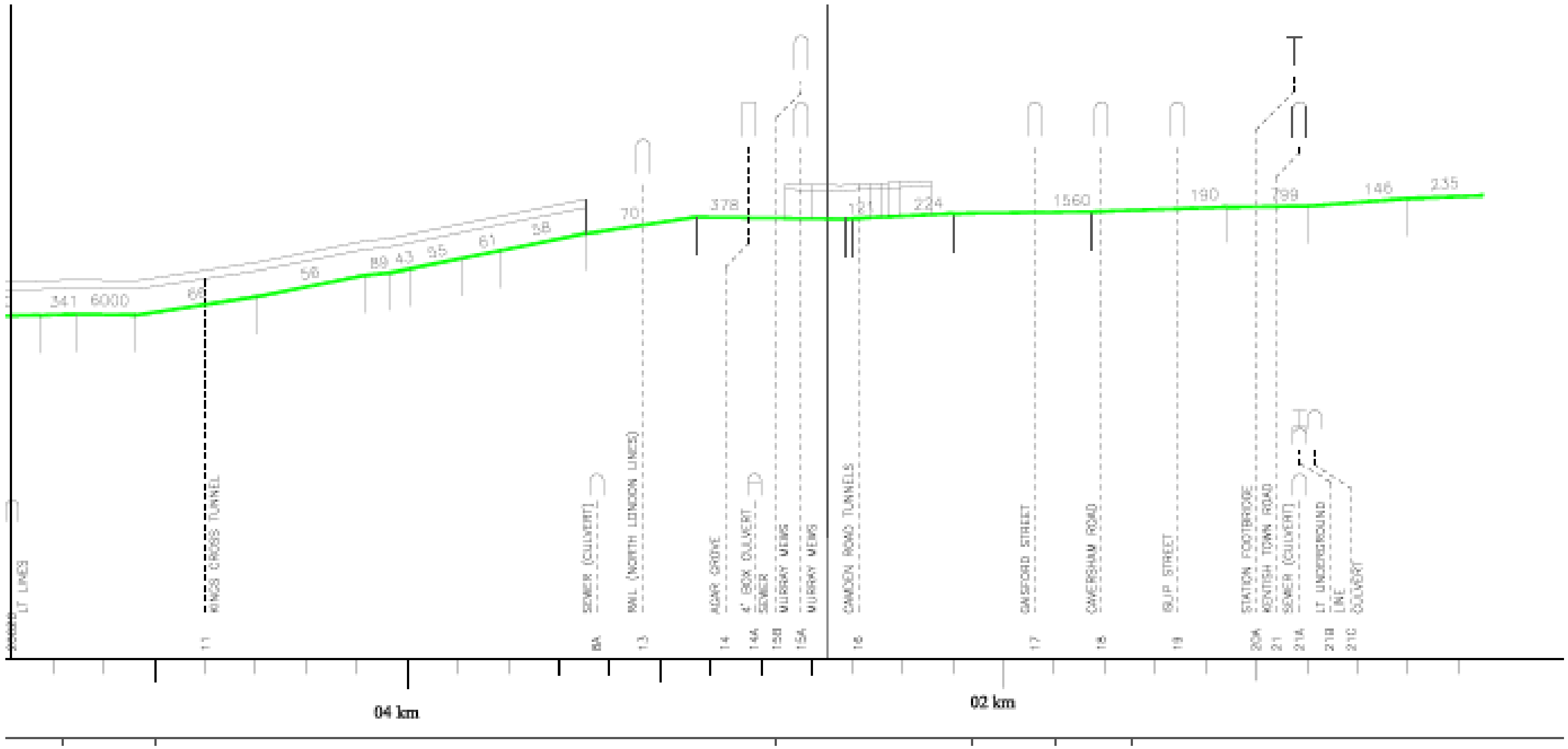


Figure 122 Gradient of the track between Euston and Kentish Town in London

Furthermore, there is no comprehensive drainage asset inventory available at Network Rail and it is impossible to accurately calculate the amount of flood water absorption in the case of flooding. At Network Rail the data concerning the exact location, condition and capacity of many drainage assets is either lost or unavailable. Consequently, many assets are unknown or abandoned and therefore not maintained. Incomplete asset data is partly available in the case study area from drawings in problematic sites provided by consulting companies who have carried out random and limited case drainage surveys (e.g. Zetica, 2007 and Network Rail, 2009). It is impossible to have the complete data of drainage systems in the area and the necessary input for inserting into the numerical model. However, some drawings show that the usual distance between the outfalls can vary between 40m and 200m. The location of outfalls in the real world is represented by sinks in the model, and because other parameters including drainage capacity per unit of length and the condition of outfalls are unknown, reasonable assumptions have been inserted into the model.

There is no information available about the area/size of the bursts. Therefore, for the mains in the area (diameter between 18” and 102”) the orifices in the pipes were assumed to be circular with a maximum of 0.15 m in diameter. Based on data from TWUL, 2017, the pressure drop equals 22m of water (almost the equivalent of 215600Pa). C_f (the coefficient of discharge) is assumed to have a maximum of 0.9. These assumptions result in a maximum discharge of 0.3 m^3/s out of the burst onto the railway track. Therefore, it is assumed that the discharge from a water main onto the railway tracks within the case study area varies between $0m^3$/s and 0.3 m^3/s. This discharge has been assumed as the initial discharge onto the sloped track over and through which the water moves towards the lowest point.

Eventually, regarding the flooding criteria, three values of $H_{max} = 0$, H_{max}=0.1m (below the bottom of the railhead) and $H_{max} = 0.15m$ (below the top of the railhead) based on the standard British Steel flat rail profiles (British Steel, 2017) were inserted into the model representing the three different criteria of flooding.

5.5.4 Tested scenarios

The following scenarios have been investigated:

1- Flood movement
2- Flood accumulation at the lowest point
3- The effect of the ballast porosity
4- The effect of the drainage system
5- The effect of the distance between the burst main and the lowest point of the track
6- The effect of the orifice size
7- The effect of the track slope

5.5.5 Results

As previously mentioned, the output from the developed model can simulate the water movement along the track and hence calculate the dependency between two urban systems by finding the accumulation of the water at the lowest point of the track. Hence the simulation results appear in two phases: 1) flood movement (front of the water) and 2) flood accumulation (at the lowest point).

5.5.5.1 Flood movement

Note that when water starts moving along the track towards the lowest point, the model runs the calculation of fluid properties at the front of the flood flow. Hence, all the results in this section indicate the properties of flood water only at the front of the flow and only until it reaches the lowest point. The calculations beyond this moment reflect the accumulation of the flood water after the front of the flow reaches the lowest point of the track and are described in the next section.

Assume that a trunk main bursts adjacent to Thameslink railway just before Clerckenwell Road, where the railway passes through a tunnel and cuttings (Figure 121). The track goes downhill for approximately L=120m with a gradient of $S_1 = 1/33$. It later reaches an uphill slope of $S_2 = 1/333$ where the lowest point of the track is located. The burst is discharging a maximum flow of $0.1m^3s^{-1}$ for 3 hours. The other parameters are as follows: d=0.3m, b=6m, $\emptyset = 0.1$, n=0.025, $Q_{sub} = 0.0001m^3s^{-1}$ and Q_{drain}=$0.002m^3s^{-1}$ at every DL=40m.

Simulating the flood water movement (Figure 123) shows how long it takes for the water from this burst to reach the lowest point of the track and to any other point between the lowest point and the burst. The water moves with the velocity shown in Figure 124. The Velocity of the water decreases with a constant slope as water moves forward before reaching any outfall where the velocity decreases considerably as drainage absorbs a significant volume of water and hence the flow decreases while the water moves. This explains the step change in the figure. The step change is also clear for the flow rate in Figure 125, which indicates a significant reduction in flow rate (the flow rate of the front water) as both local drainages (i.e. shown as step change) and the subgrade layer absorb some of the flood water (shown as gradual change). Again, significant reduction is observed in the location of the outfalls. As water moves along the track, every segment of the ballasted track becomes saturated towards the end (the lowest point of the track) and hence some water stands on saturated segments and flows into the next one. This continues right until all segments saturate and accumulation starts at the lowest point. Figure 126 shows this water height along the track towards the lowest point. Because the flow rate decreases as water flows further from the burst, the height of the water standing on segments also decreases (The Manning equation shows a direct variation between Q and h as well as between Q and U.)

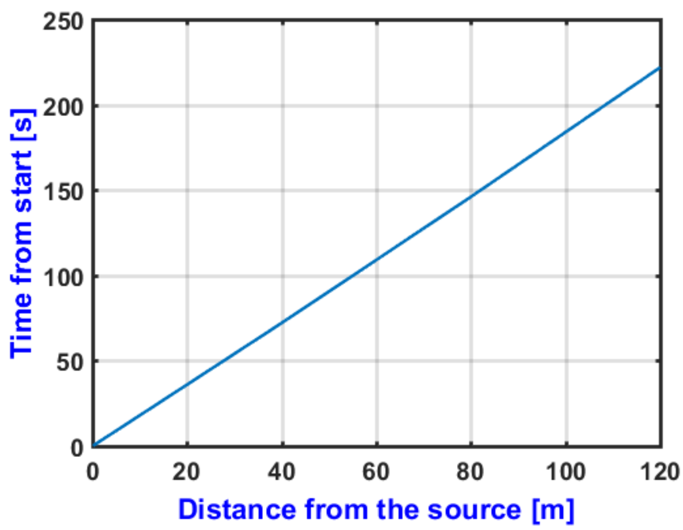


Figure 123 Time of flood movement along the track (front of the flow)

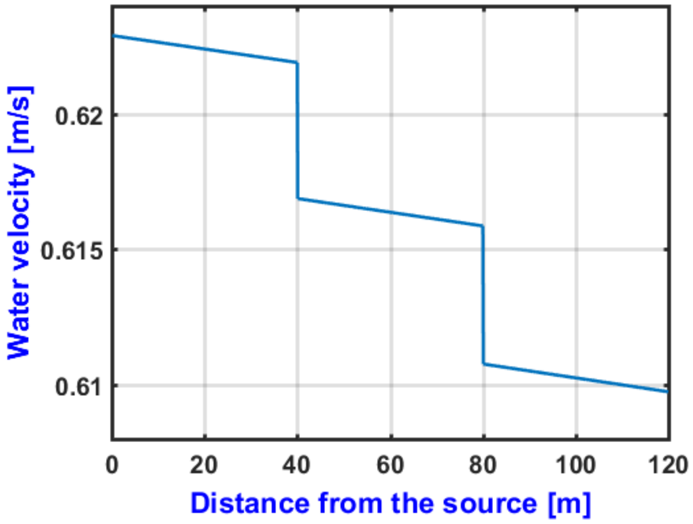


Figure 124 uniform steady velocity of the water above the ballast in the direction of the flow

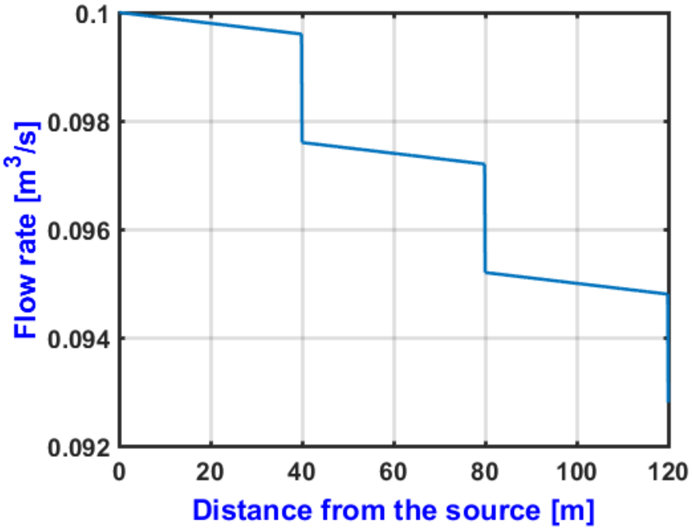


Figure 125 Flow rate at the front of the flood water

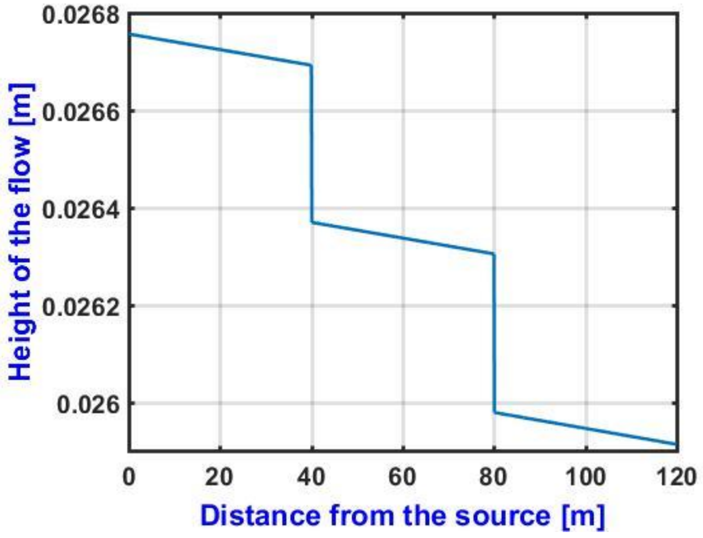


Figure 126 Height of the flood along the track just before the accumulation starts

After the flow eventually starts accumulating at the lowest point of the track, that is where the actual flooding scenario occurs, and it can impact not only the track structure or railway infrastructure but also the railway operation. The next section of this study focuses on this impact.

5.5.5.2 Flood accumulation

Taking the exact same flooding scenario near Clerckenwell Road, Figure 127 shows how quickly the height of the water increases and exceeds the critical flood height (say 0.15m) for trains being allowed to run well before the flow of water from the burst would even be stopped (the end of the simulation= 3hours).

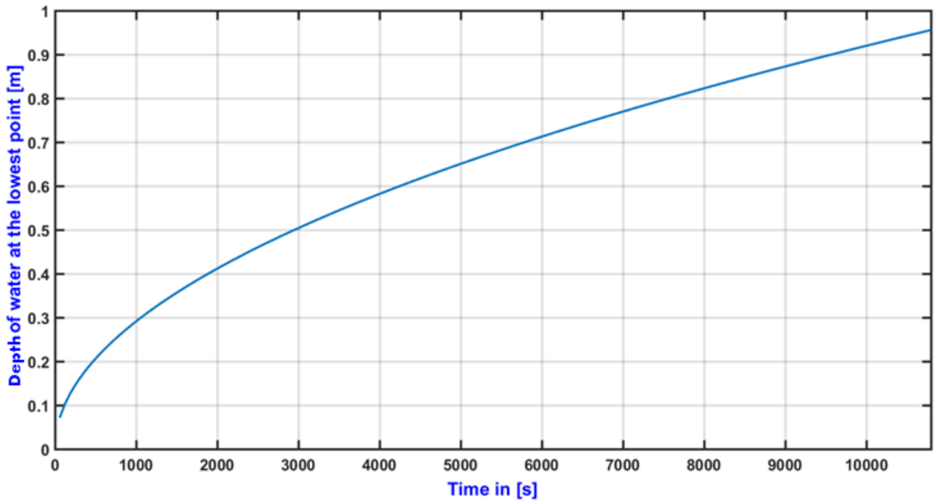


Figure 127 Height of the water at the lowest point of the track in time

Although on its own the flood accumulation at any point of the track including the lowest point is important, because this study aims at understanding the impact on the running of trains, it is necessary to first focus on the critical points of the track and then define the appropriate metrics for investigating dependency. The metric is supposed to relate two systems in connection with the same risk scenario. Also, since this risk scenario has an impact on the operation of the railway, the metric is required to reflect this impact. Furthermore, considering the standard procedures for the operation of trains through flood water and the discharge from a burst, "track flooding time resulting from trunk main burst discharge" has been defined as the dependency metric. This metric indicates the time length for water from a burst to flood a track at a vulnerable location, which would be the lowest point of the track.

Taking the same burst near Clerkenwell Road, Figure 128 indicates that when water flows 0.023 m^3s^{-1} from a burst in a trunk main adjacent to a railway track, it takes about 65 minutes for the water to accumulate below the top of the railhead (h=0.15 m) at the lowest point of the track. It clearly takes a shorter time for the burst water to accumulate below the bottom of the rail and below the bottom of the railhead (H=0.0 m and H=0.1 m respectively) and a longer time to accumulate higher (H=0.25m). The results also show the effect of a burst or the amount of discharge on the track flooding time. Note that for Thames Water, whose trunk mains carry water with an equivalent pressure head of ~21-22m (~215KPa) a discharge of 0.023 m^3s^{-1}flows out of a circular orifice with a diameter of ~0.04m.

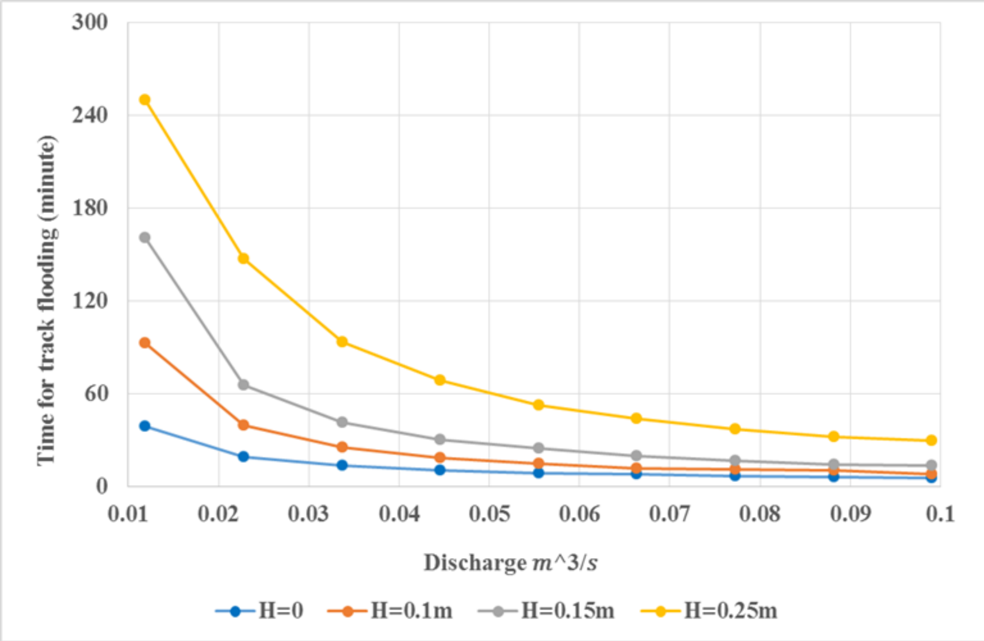


Figure 128 Track flooding time for different flooding criteria

Furthermore the simulation demonstrated that the scenario parameters, namely the ballast porosity (∅), the drainage arrangement (shown by DL), the distance between the burst and the lowest point of the track (L), as well as the gradient of the track at the side of the burst S_1, can significantly affect the track burst-induced flooding time.

To begin, it is necessary to investigate the effect of natural drainage (drainage through ballast and the subgrade layer) on the flooding. Ballast track, a granular material, is still the most common railway load bearing structure. The thickness of the ballast layer is usually 0.25-0.3m. The properties of new ballast, including its shear strength and permeability, are different from those of older ballast. These properties change progressively because of breakage, erosion and fouling. Fouling reduces the permeability of ballast layer and therefore decreases the natural drainage (Indraratna et al., 2006).

The permeability of the ballast has been incorporated into the model using a “porosity” parameter, which is defined as the fraction of the volume of voids over the total volume of the ballast. It is assumed that the porosity is uniform all over the track.

5.5.5.3 *Effect of ballast porosity*

Figure 129 shows the effect of the porosity of the ballast on the track flooding time for the same case study on Clerkenwell Road, assuming H=0.15m is the track flooding criteria. Obviously when the ballast is old (the porosity/ permeability is decreased) it takes a shorter time for the track to be flooded. Again, the effect of the discharge (and hence of the burst size) must not be ignored. For a larger discharge, little difference is observed in the curves and the track may be flooded in less than an hour's time for almost any ballast porosity.

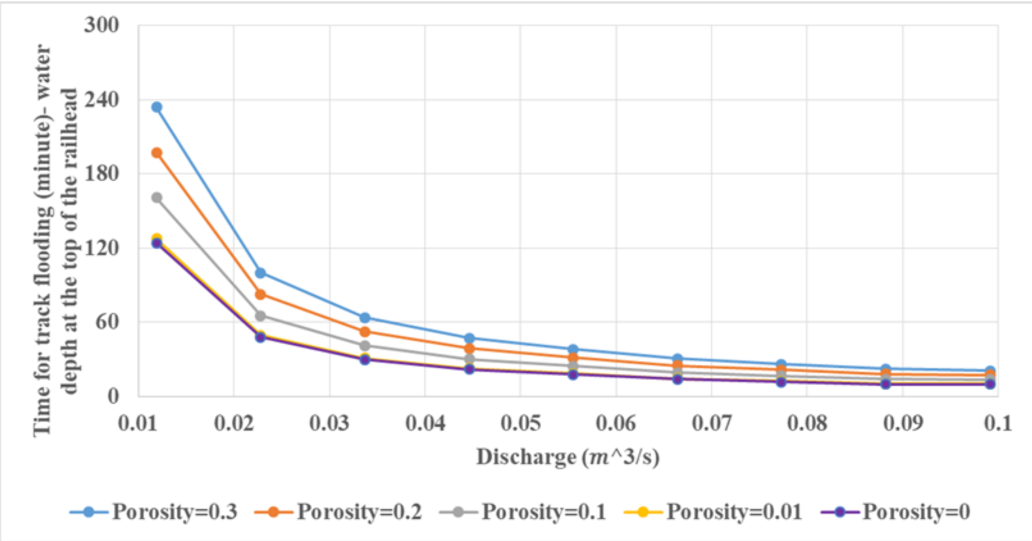


Figure 129 Effect of ballast porosity on burst-induced track flooding time - water depth below the top of the railhead

This shows the significance of the drainage mechanism under the track. In many actual cases the railway drainage is blocked or abandoned and cannot be maintained because of the short track possession time available for planned engineering works, especially in urban areas where lines are congested. Furthermore, some railway systems have little or no understanding of their drainage asset inventory because their railway network is complex in terms of its diversity and spatial distribution. Also, in the past there were examples of a lack of drainage in the case study area.

5.5.5.4 *Effect of a drainage capacity*

Figure 130 shows the effect of the drainage capacity at the site when a burst occurs in the same case study mentioned above. The results show that discharges greater than

0.1 m^3s^{-1} are large enough to flood the track regardless of whether a drainage system is present or not.

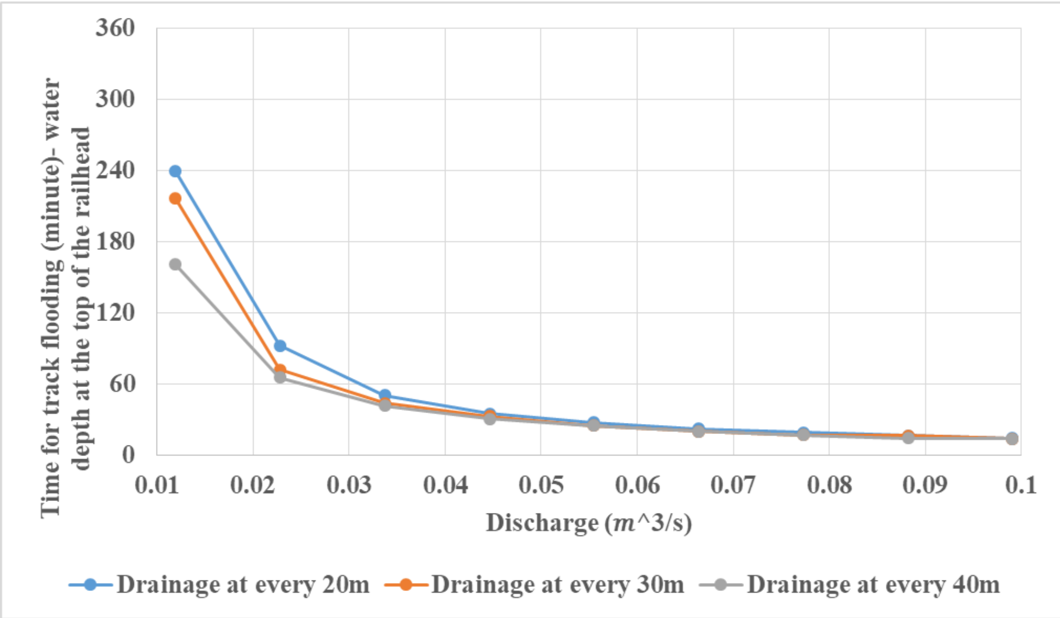


Figure 130 Effect of drainage system on burst-induced track flooding time

5.5.5.5 Effect of distance between burst main and lowest point

In order to study the effect of L on track flooding time, assume a different burst scenario which might happen between King's Cross tunnel and Agar Grove (between 3.5 km – 4.6 km after Moorgate station which is located at 0.0 km). In this case, the track passes over a number of different gradients with the lowest point of the track located just before King's Cross Tunnel. Hence, the model needs to takes into account the effect of different slopes if the burst happens anywhere further from the first gradient right next to the lowest point. Figure 131 shows the effect of the distance between the burst and the lowest point while the track gradient is varying. This scenario assumed that the criterion for track flooding is H=0.15m (flooded below the top of the railhead). For L=500m $S1-1=\frac{1}{89}.S1-2=\frac{1}{56}\ and\ S1-3=\frac{1}{66}$, for L=400m $S1-1=\frac{1}{56} and\ S1-2=\frac{1}{66}$, and for L=200m $S1=\frac{1}{66}$.The other parameters are as follows: d=0.3m, b=6m, $\emptyset=0.1$, n=0.025, $Q_{sub}=0.0001m^3s^{-1}$ and Q_{drain}=0.002m^3s^{-1} at every DL=40m.

The results show that while it clearly takes less time for the track to be flooded when the burst occurs nearer the lowest point, when the discharge is large (>0.1m^3s^{-1}) the flood height reaches the limit in less than an hour's time and no significant difference is observed between the time lengths for track flooding (Figure 131).

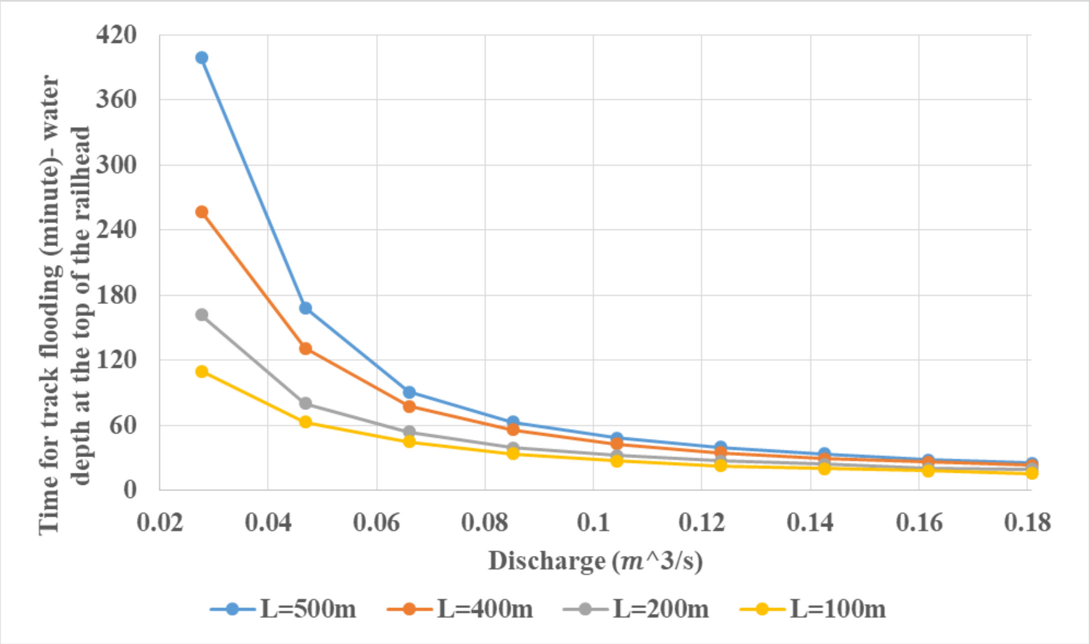


Figure 131 The effect of distance between burst main and lowest point of the track on track flooding time (gradients varying)

5.5.5.6 Effect of orifice size

Figure 132 highlights the effect of the size of the burst on track flooding. For orifice sizes larger than 0.1m diameter, it takes less than 15 minutes to flood the lowest point of a track when the distance between the burst and the lowest point varies between 100m and 500m.

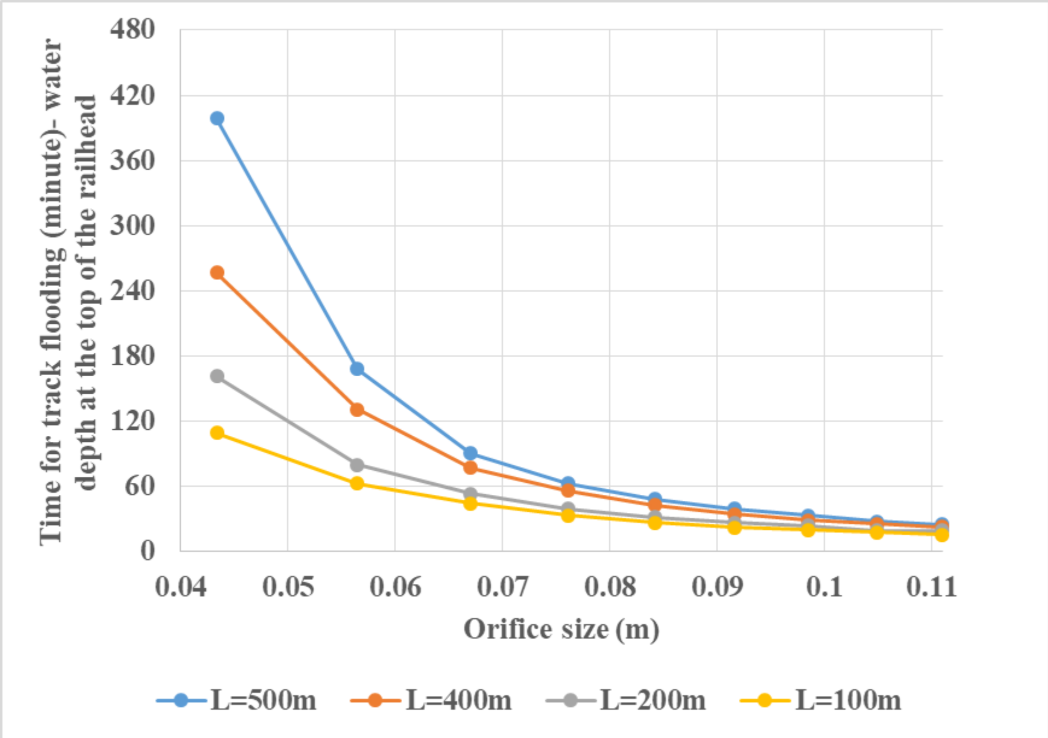


Figure 132 Time of track flooding for different orifice size

5.5.5.7 Effect of track gradient

Although the routing and railway gradient are usually the concerns of the traction of a railway, the simulation results showed that the effect of the gradient alone on the water movement (regardless of distance effect) cannot be ignored. Assume a fictional burst scenario in which S_1 varies while all other parameters are constant and as follows: L=120m, d=0.3m, b=6m, $\emptyset = 0.1$, n=0.025, $Q_{sub} = 0.0001m^3s^{-1}$ and Q_{drain}=0.002 m^3s^{-1} at every DL=40m and $S_2 = 1/333$.

Figure 133 shows the effect of the railway track gradient on the time length for track flooding. When the railway track is almost flat (gradient equals 1/1000) the time length for track flooding is significantly longer. And when the railway track is steeper at the side of the burst, the time for burst-induced flooding is shorter.

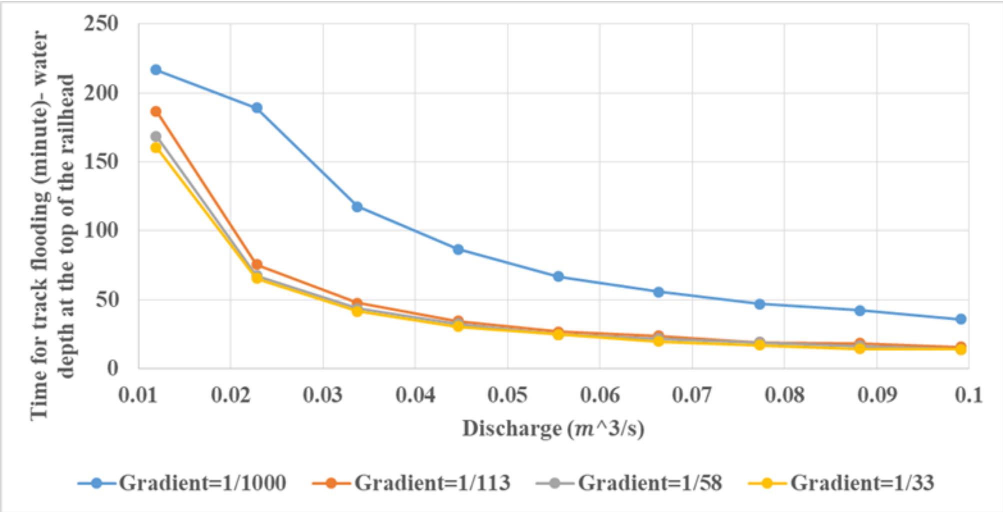


Figure 133 The effect of railway track gradient on time for burst induced track flooding

5.6 Discussion

The proposed evaluation approach has been described and exemplified effectively in a real-world case study. The case study demonstrated the value of a quantified modelling tool in investigating the impact of parameters related to the components of two different infrastructures on the dependency cascade scenario. It is argued that without an evaluation framework that includes the knowledge of experts and relevant physics-based modelling tools:

1. Cross-sectoral risk scenarios would not be well understood and not be taken into account as interdependency problems. Moreover, using a traditional silo approach towards risk, the sectors on their own are unable to even identify the shared risks in the first place. An example of the silo approach toward managing infrastructures in this case is the consulting work carried out for Network Rail to find out the problem of the drainage system failure near the Kentish Town area in 2007. Detailed and extensive inspection was carried out and results were reported without any major findings about the issue of the drainage system failure (Zetica, 2007). In 2017, in the workshop held for experts from TWUL and NR for this research, it was revealed that the entire drainage system in the area is connected to an abandoned sewer system which is not maintained at all. This emphasizes the necessity of engagement with

experts and collaboration of sectors to find a more holistic approach towards the failure of interdependent infrastructures.

2. Because the impacts/consequences of the risk scenario are not quantified, the effects of different components of infrastructures on their operations are more likely to be underestimated.
3. Vulnerable locations of the railway track cannot be identified, and hence the information, although very critical, cannot be used for future decision making of companies.

Furthermore, since the output of the tool is generic and focused on the height of flooding (a well-defined flooding metric for the railways) and mains discharge (a controllable parameter for the water system), higher order (indirect) dependencies can be captured. Such dependencies may include railway service delay minutes and ballast maintenance because of burst induced flooding as well as the water company's cost benefit analysis of trunk main repair and condition monitoring. The tool is simple enough to both be integrated into other modelling tools and be demonstrated on its own. The impact of the scenario on the other railway structures or components (e.g. signalling, track pieces and bits and third rails) can be quantified using exactly the same principles and the concept of flooding height.

In the parametric study it was observed that some parameters affect the flooding time more than others. For instance, in general the parameters related to the burst discharge affect the flooding time more than parameters related to the track. In a typical case study scenario (Clerckenwell Road), if the size of a circular hole in a trunk main increases 10 times (e.g. from 8mm to 80mm) the discharge value increases by approximately 100 times and this speeds up the flooding time below the top of the railhead by approximately 300 minutes. Clearly the longer the flooding time, the less severe the flooding scenario is. Since even a few minutes are significant for the running of trains, this example shows why such a tool is needed to show how sensitive burst induced flooding is to the flood parameters. The results clearly show that when the burst discharge is very significant (normally above 0.1 m3/s), no significant difference is observed between the effects of any other parameters on the time for the track to flood. For discharges below 0.1 m3/s, if the distance between the burst and the lowest point doubles, the time for track flooding increases by an average of 120% to 140%.

Regarding the porosity and drainage systems, the effect on the time for track flooding is not significant for any discharge larger than 0.03 m^3s^{-1}. In discharges smaller than this amount, the more porous the medium is, e.g. double or triple the porosity, the longer the time usually increases, e.g. by 120% to 140%. With regard to the drainage, assuming the current drainage capacity (including the capacity of each drain and the number of drains along the track) no significant difference was observed in the time for track flooding in discharges above 0.02 m^3s^{-1}. In discharges below this, when the drainage capacity doubles, the time for flooding increases by 150% . This shows that first the current drainage capacity cannot cope with large burst induced track flooding. Moreover, it may also suggest that the best way to mitigate smaller burst induced track flooding is to increase the drainage capacity. Furthermore, the results showed that, in general railway parameters have little effect on track flooding time if the discharge from the burst is larger than 0.1 m^3s^{-1}.

The results also can help to find critical and vulnerable flooding locations. In general, the steeper the track gradient and the less distance between the burst and the lowest point of the track, the quicker the track flooding time (i.e. the more severe the flooding). These results can be integrated into a city level GIS system to demonstrate both the severity and the location of the floods. This can facilitate the understanding of external risks (transport disruption) caused by an internal failure (e.g. a water main burst). The results can also help railway system operators facilitate the decision-making process in terms of drainage policy and maintenance activities.

To summarise, this chapter describes a tool that has been developed to evaluate the scenario of track flooding caused by a water main burst and to quantify the dependency of the operation of a railway system on such flooding. The model and results can aid the prioritisation of investments and risks as well as enable the optimisation of maintenance activities for both railway and water companies by providing a quantified measure of the interdependency between the two. The developed quantified framework can facilitate characterisation of a specific dependency that exists between two infrastructure systems, namely an urban railway and trunk main network at operation level. It first identified the general disruption scenario that creates a dependency which is not evident while urban systems are operating normally. The study later quantified this dependency by introducing “time for track flooding due to burst discharge" as a metric and carried out a parametric study. The results showed that parameters such as the distance between the burst and the lowest point of the track, the gradient of the flooded track, the permeability of the ballast and the capacity of the drainage affect the time for track flooding and hence the operation of the railway. However, the discharge from the trunk mains (source of the flood) plays the primary role in impacting railway operation.

Chapter 6 Discussion of this thesis

This thesis argued that complex behaviour of infrastructure systems in relation to one another can be investigated and understood effectively if the operators, owners and experts of infrastructures are engaged in the process of identifying and evaluating infrastructure interdependencies. Incorporating the knowledge of experts into modelling, simulation and tool development in a scenario-based, case specific approach provides invaluable insights and benefits for researchers and academics. This chapter presents an overarching discussion regarding the implications of research findings for the study area, and practical implications for industry by considering the overall approach of this research, its elements and the existing limitations.

6.1 The overall approach employed by this thesis

Regarding the overall approach of this thesis towards investigating dependencies (as outlined in Figure 30), several benefits can be observed. Benefits and recommendations regarding the employment of the approach introduced by this thesis is explained in this section.

Firstly, whereas a traditional literature review (as shown in Chapter 2) usually reveals gaps that need to be bridged from the viewpoint of academics (as the review is limited to academic sources), practitioners can help to reveal gaps of knowledge regarding quickly evolving, highly complex systems that were absent in the academic literature (as discussed in Chapter 3). The poorly known dependencies identified through a participatory-based approach in Chapter 4 and Chapter 5 are either fully absent as a research subject or as an infrastructure dependency-related concern from the academic literature. It can be argued that the exploration of poorly known dependencies is essential for highly complex systems such as railways, where the pace of development due to increasing demand exceeds the pace of research and the evaluation of changes. Also, both case studies could identify serious vulnerabilities regarding the dependencies of infrastructure systems at an operational level (refer to sections 4.6 and 5.5). Discovering new gaps could be a major challenge for the researchers in terms of scenario development, data collection, modelling assumptions and validation of the methodology since there is no previous data, models or results to refer to. However, it can be argued that such efforts (e.g. this thesis) into discovering and academically evaluating poorly known infrastructure dependencies, paves the way for future research projects.

Another benefit of the overall approach arises from the ability of experts to provide details that are necessary for understanding dependent behaviour at a technical level. When considering how various systems depend on each other, engaging with different stakeholders can help clarify specific details that can highly impact the dependency scenarios (e.g. biomass storage issue in section 4.6.2.8 and the amount of discharge out of the burst in section 5.5.2). Such details cannot be captured during desk studies from academic and other publicly available sources. In addition to the details required for scenario development, experts can also significantly contribute to the interpretation of research findings. For instance, the analysed commodity movement and electricity generation data (in section 4.7) would have not been interpreted as comprehensively if this research lacked expert consultation. Moreover, crosschecking details inside and across sectors as well as the feedback loops between the elements of the proposed approach (e.g. between "case study selection" and "identifying experts" as shown in Figure 30) act as two effective mechanisms to ensure the assumptions were reasonable for dependency scenario development and later, its quantification (through analysis, modelling and simulation).

Furthermore, note that the thesis applied an overall approach (as suggested in section 3.5) that uses a scenario-based case study method that incorporates knowledge of experts from the very early stages of the research. Hence, the thesis acts as a great example, demonstrating that methods for investigating infrastructure dependencies are not limited to common existing categories of approaches (i.e. empirical and predictive) as outlined by the academic literature (reviewed in Chapter 2 and presented in Figure 19). Note that both empirical and predictive approaches were acknowledged as useful elements of this thesis through analysing the pattern of past commodity movements to power stations (Chapter 4) and developing a predictive tool for burst induced flooding (Chapter 5). However, this thesis suggests that a comprehensive framework for investigating infrastructure dependencies includes many elements and processes prior to the modelling and simulation stages (refer to Figure 30). This novel framework is not necessarily implying what kind of modelling and simulation should be used to produce meaningful and useful results. The framework rather suggests that, to be more pragmatic at researching high-priority interdependencies, it is best to engage with experts on a scenario basis. Requirements for an infrastructure dependency research and its desired models and tools should be extracted first, since experts and researchers should collaboratively find out the most practical and useful outcome and the most appropriate tools and modelling strategies that support the scenarios of their shared concern.

Furthermore, as the framework presented in Figure 30 graphically implies, the two main entities of "information, concerns and needs" as well as "modelling, analysis, results, tools and validation" are of equal importance when investigating dependencies at a technical environment. This suggestion is fully absent from the available academic literature in this field (as reviewed in Chapter 2). From observation, it is evident that all studies either focused merely on the first entity (e.g. conceptual studies as reviewed in 2.1.1) or started the investigation from the stage of "data collection and analysis" almost ignoring previous stages outlined in the framework of this thesis (e.g. the studies reviewed in 2.1.3 and 2.2.2). Although some studies partly included knowledge of experts in infrastructure dependency analysis (as discussed in section 3.1) no research is seen to assign equal importance to participatory elements or modelling and simulation. This thesis has tried to demonstrate the significance of both entities and their capability to add to the knowledge of railway interdependencies. Hence, both the outcome and the framework (and its application) can be considered as a novel contribution to the academic literature in this field.

Note that the framework and the overall approach suggested in this thesis demonstrates enough flexibility and integrity at the same time to be used for dependencies across various infrastructures (i.e. other than railways) as it involves experts bringing the best available knowledge to understand a dependency scenario that they deal with. For instance, the case study in Chapter 5 demonstrated a complex urban infrastructure dependency problem that could be well understood by relying on the judgement of experts to define the scenario and the modelling input. Therefore, the same approach would be effective for investigating other poorly known complex urban infrastructure dependency scenarios such as; the effect of water or gas leakage on roads, the impact of change in ground water levels on maintenance of railway tracks etc. On the other hand, Chapter 4 demonstrated a potential supply chain risk due to interdependent infrastructure systems at a detailed-scenario level. Dependency scenarios of a similar kind, such as the dependency between port traffic and other manufacturing industries (e.g. steel) and the potential capability of the rail and roads to absorb disruption shocks, can be evaluated using the same approach (e.g. collecting consensus on the scenario details and analysing operational data).

Using the same overall approach for both case studies, the two dependency scenarios can reveal certain characteristics of the approach outlined in section 3.5. Whereby the freight railway and power sector case study focused on the past and current dynamics between the interconnected systems in an industrial region, the case of a burst-induced railway flooding focused on the predictive flow behaviour in an urban area. The generic framework of this research offered adequate flexibility and robustness to be employed by both studies (presented in Chapter 4 and Chapter 5). Since the case study presented in Chapter 4 is an example of a regional and industrial normal operation, collecting information, concerns and needs regarding the overall scenario could be completed by engaging with a large and diverse group of stakeholders who are familiar with all aspects of the industrial region and its operations. However, in the case of the localised flooding scenario, there were very few specialists who had the technical capability of understanding burst-induced flood water behaviour in urban railway premises. Therefore, the comparison of the two case studies showed that, generally for more engineering/technical dependency scenarios, the elements of the generic framework cannot be necessarily supported by a large and diverse group of stakeholders but through engaging with a few stakeholders who are highly knowledgeable regarding the specific scenarios. Although the overall generic framework can be employed for the investigation of different types of infrastructure dependencies, the details regarding the application of the individual elements largely vary depending on the nature of such dependencies.

There is no evidence of any existing academic research that investigates a research question regarding “how two technical infrastructure systems are dependent on each other” from a very conceptual stage to a detailed technical stage using a combination of participatory-based modelling, data management and analyses, modelling and simulation and validation. No previous efforts have been made to conduct engagement sessions in the early and hypothetical stages of investigating technical infrastructure interdependency where the outcome of such engagements are directly and iteratively used to quantify a poorly known dependency for a complex system that is vulnerable to (and can create) a diverse range of cross-sectoral risks. This thesis argues that the reasons underlying such gaps in the academic knowledge of infrastructure dependency may include:

A significant portion of what is known as the academic knowledge of infrastructure interdependency remained at a conceptual level for decades most likely because of the extensive scale of interdependencies. Researchers only quantified those dependency scenarios that have been strategically important at a national scale (for economy, welfare, security etc) or those which simultaneously; are more likely to occur, directly affect the normal operation of systems or cause major consequences. However, there are many dependency scenarios that are less likely to occur that cause major consequences for a complex network of infrastructures (e.g. an urban system) through a sequence of case specific events (e.g. long-term disruption of freight railway traffic as explained in Chapter 4).

The process of engaging with experts (e.g. from different sectors/infrastructures) to investigate details of poorly known dependency scenarios is challenging and time consuming (some of these challenges are highlighted in section Challenges and limitations). Most of the research reviewed in Chapter 2 of this thesis, replaced such efforts with limited desk studies, either because the scope of their research projects was limited (e.g. in terms of time) or they were not aware of the possibilities and capabilities of adopting a participatory-based approach (which is well-known in the field of environmental engineering) to investigate infrastructure dependency.

However, this thesis demonstrated that:

- A combination of engaging with industrial practitioners and the quantification and evaluation of case specific dependency scenarios, can effectively advance the academic understanding of infrastructure dependency by quantifying the degree of dependency between several critical sectors and creating a generic dependency evaluation tool. Hence, this thesis demonstrated that, with the help of practitioners, academic researchers can proactively develop useful results, metrics and tools to aid the resilience of increasingly interdependent infrastructure systems.

- The concerns and needs of industrial practitioners regarding infrastructure dependencies and cross-sectoral risks can be largely different to those included in the current academic knowledge. The only effective mechanism to bridge such a gap is to more extensively involve industrial experts in research decisions such as problem scoping and modelling and simulation.

6.2 The individual elements of the approach

In addition to the implications relating to the overall approach, several arguments and suggestions will be made in this section regarding the individual elements.

As for identifying and engaging with stakeholders and experts, the author of this thesis mainly consulted railway asset managers, as well as asset engineering and business continuity experts in the very early stages when the scope of the research was yet unclear. It can be argued that identifying and approaching a different group of stakeholders would have revealed other types of dependency or cross sectoral risks. The cross-sectoral risks highlighted by experts originated from concerns of practitioners, and these concerns largely vary across a complex system such as railways. It is also argued that the structure of the organisations and companies who manage sectors not only influence the way stakeholders react in a shared disruption situation, (i.e. some companies have more structured shared contingency plans) but also influences the concerns and hence the dependencies expressed by stakeholders. For instance, if geographically dependent systems have a robust contingency plan/behaviour for flooding, or a strong defence in depth mechanism for fire, they may express more concerns regarding human errors etc. which contribute to shared risks. Therefore, this research recommends that by focusing on case studies and specific scenarios, researchers can uncover a very diverse range of high priority poorly known local-level dependencies for the railway systems across the world which are all complex (i.e. one might be very different to another regarding their dimensions of complexity). This indicates why this thesis essentially focuses on the term “scenario” when investigating dependencies for a sector/infrastructure, especially when they occur in a technical environment (as opposed to an economic environment).

Moreover, it is important to acknowledge that stakeholders and experts (who support academic research) have concerns and interests outside of the scope of the research project. This can cause conflicts during problem scoping or when agreeing on details of the case studies and dependency scenarios. Although, this can positively reveal a higher number of dependency scenarios for further academic investigation, it can cause major delays for completion of academic research. To avoid conflicting targets, it is recommended to agree on an initial scope as a baseline with practitioners across sectors and organise joint meetings to clarify such baselines. Also, it is suggested that the scope of the dependency scenario and the case study should be decided well before deep engagement sessions such as workshops where participants are supposed to be fully engaged in making informed decisions regarding the input for a model or tool. Although a trial and error method in general is encouraged during engaging with experts, it is suggested that researchers must avoid errors that cause time consuming, difficult to organise and costly processes such as running repeated workshops.

Moreover, during deep engagement sessions it is important to manage distractions away from the main targets as well as disruptions due to any out of scope discussions. One effective strategy in managing this issue is to choose a sufficient but not redundant number of participants. It is also crucial to leave time for a discussion session at the end of a deep participation session (e.g. workshop) to allow experts of different sectors to communicate and network regarding the topics of interest as a side benefit for them.

One might argue that because participatory modelling is a common industrial approach for different purposes (e.g. finding systemic behaviour of a newly adopted signalling sub-system for a railway system) practitioners would be independently capable of investigating dependencies across infrastructures without the support of researchers. This thesis argues that the boundaries of technical infrastructure systems are not necessarily well managed and technically owned by infrastructure owners. Also, all the participatory-based activities across industries are motivated by (and hence limited to) certain business needs (bounded by time, resources etc.). Hence, rarely any effort is observed to develop a cross-sectoral evaluation tool considering academic robustness such as that developed in Chapter 4 and Chapter 5 of this thesis. Therefore, industrial practitioners require academics' support to make decisions in identifying and investigating poorly known dependencies. Small and large engagement sessions during an academic research process provide a great opportunity for experts across sectors to share knowledge, start collaboration and initiate projects that were ignored in the past.

Last, this thesis is not suggesting any strict structure for holding deep engagement sessions (e.g. workshops) to study infrastructure dependencies in a technical environment. The main workshops held for this research showed that details such as rules of engagement, structure of the exercises, methods of collation and documentation during a deep engagement session largely vary based on the nature of the investigated scenarios and the type of participants. For instance, the scope of the railway and power dependency workshop required several group-works as well as assigning leaders and note takers for the groups, whereas the burst-induced flooding workshop required a smaller sized engagement while the author attempted to collect all the detailed output precisely (e.g. parameters for modelling) and to record the session.

As for the analysis, modelling, simulation, results and evaluation being important elements of this thesis, several arguments can be made. For the first case study, past data analysis could provide useful quantified results to demonstrate a qualitatively known dependency in a normal operating condition, whereas for the second case study, developing a generic and predictive tool could contribute to academic knowledge and industrial practice. Both case studies supported quantification of poorly known dependencies through suitable metrics that could successfully relate to the nature of the dependency scenarios investigated. The railway and power case study (Chapter 4) could reveal patterns that explain how the electricity generation could be dependent on the train movement. Whereas the case study related to railway and water (Chapter 5) could parametrise the burst-induced flooding scenario. The data analysis for train movement and electricity production could be cross-checked and verified using other data and consulting experts, whereas the flooding modelling and simulation could be validated using sensitivity analysis and laboratory experiments. Note that in both cases the academic robustness and integrity were ensured, and all the quantified results and the generic tool developed could be considered as a significant academic contribution.

Regarding the benefits for industrial practitioners, the first case study presents figures that strongly demonstrate the significance of railways as well as the vulnerability of the power production sector in terms of a dependency between the two. Such results can be used by practitioners of both industries as supplementary evidence to effectively demonstrate the potential vulnerability of their systems for different purposes such as justification of future business grants for resilience projects. The second case study provides a user friendly and generic tool (including a visual and easy to use interface) that can be used by water and railway companies to calculate the impact of localised flooding on their systems. By providing the time for track flooding according to the effect of various parameters, railway companies could make better informed decisions regarding prioritising their maintenance activities to support their drainage assets at vulnerable locations. Also, water companies could realize the impact of their failures along a railway track and the significance of shortening flooding time and could take immediate actions to stop such flooding. To summarise, results, figures and tools not only specify vulnerabilities and evaluate poorly known dependencies for sectors but could also be used as a means for encouraging investment on certain neglected areas of the business (e.g. drainage).

6.3 Challenges and limitations

Regarding the challenges and limitations of this research, this section includes the relevant arguments and recommendations.

In general, it can be argued that since complex systems are fundamentally defined as interacting elements inside traditional boundaries, it is challenging to evaluate events across these boundaries. Several observations can confirm this statement. Firstly, literature showed that the connections across infrastructures are well understood only in scenarios that directly and frequently affect the normal operation of the systems (e.g. electricity provision). Also, as infrastructures evolve and become more complex, a high number of cross-sectoral scenarios appear that have not been evaluated properly. Next, engaging with experts showed that the boundaries of two complex systems is not fully understood, owned or managed (in terms of vulnerabilities) by either of the two infrastructure owners operating those systems. Also, the vulnerabilities which can potentially result in cross-sectoral risks usually arise from poorly managed sub-systems or elements of individual infrastructures (e.g. drainage) for which a comprehensive and useful data is unobtainable. Hence, it can be argued that to increase resilience across infrastructure systems, both management of internal sub-systems and boundaries of the systems require improvement. The second case study of this thesis clearly demonstrated this argument by showing a physical dependency between a railway drainage and a sewer sub-system (of a water system). The overall thesis carried out a robust investigation to improve the knowledge of those railway dependencies that impose vulnerability to railway operations and decrease its level of resilience.

Furthermore, a challenge is observed regarding finding, collecting, analysing and interpreting data when investigating interdependencies. Firstly, when the past anecdotal and actual data related to sectors are needed for pattern analysis (as shown in section 4.7), it is highly unlikely that any ready-to analyse dataset can be easily accessed and used. In many cases, the relevant dataset needs to be collected, refined, filtered and processed for a long time before it becomes useable for dependency quantification. For instance, University College London collected the processed railway TRUST data on an online internal dataset system using different data management techniques (e.g. SQL). The prepared data could later be used for investigating dependencies only with the support of experts interpreting the terms, units and quantities included in the dataset as they were very sector and even company specific. Such extensive efforts for only the preparation stage of the dataset used for dependency analysis are usually hidden in the background of interdependencies related research projects (like this thesis). However, an argument can be made that such efforts need to be acknowledged as a major challenge for studying newly investigated dependency scenarios. While datasets such as NISMOD as part of ITRC initiative (as described in Chapter 1 and 2) are required for large scale national scale dependency scenarios, it is suggested that more specific, case and scenario-related datasets such as FTDMS by UCL should be developed for investigating sector-specific dependencies at a local/regional and finally national scale. A comprehensive ready to use dataset that includes past train movement data across the UK could be a very beneficial tool for investigating many railway dependencies highlighted in this thesis. Such a dataset could potentially facilitate future research regarding the degree of vulnerability and dependency of railways in a diverse range of scenarios including bridge strikes, weather effects and bus/truck replacement services, by describing the pattern of railway traffic as an element of the above scenarios. Regarding the dependency between railways and water sector, this thesis suggests that the data relating to the vulnerability of water supply network to burst can support further dependency analysis in Chapter 5 by providing input for a burst-induced flooding risk evaluation tool. Although such datasets are most likely to exist at a sector level, this research found that it is challenging for the academic researchers to access any data regarding vulnerability of systems due to security issues and the high sensitivity attached to infrastructure systems.

As for the other challenges faced during this research, the dependency scenario realization even at a qualitative stage is a major challenge. This is mainly because a dependency scenario related to two infrastructures includes so many technical and human elements that interact in complex ways, meaning that experts might have contradicting information about them. For those dependencies that are modelled and simulated at the quantification stage, each element or interaction could act as a significant parameter or variable (e.g. how long water companies take to stop the flow out of a burst) that can significantly affect the modelling assumptions. It is recommended that assumptions regarding the quality of a scenario need to be confirmed with experts during "scenario development sessions" prior to discussing quantities during a "workshop session" at the beginning of which, the qualitative scenario is briefed to participants to avoid any wrong assumptions.

6.4 Further recommendations and the conclusive argument of this thesis

Regarding past research, this research project contributed to the body of academic knowledge by producing more sector-specific and engineering metrics for interdependency analysis for a highly complex system (refer to Figure 18). Rail is a diverse, spatially distributed, variable, complex and adaptive system which has numerous dependency scenarios with other infrastructure systems that have been largely ignored. The metrics produced in this research could be further translated to create more metrics that suit other engineering and decision-making purposes. For instance, by expanding the scope of the railway water scenario as presented in the case study in Chapter 5, additional metrics such as the number of trains and passengers affected by a flooding disruption, delayed minutes, reputation damage and cascades across rail networks can be produced in future research. However, this thesis suggests that the practicality and usefulness of such metrics for industrial practitioners needs to be discussed with them to increase the positive contribution academic research can make. In both case studies in this research, metrics were developed according to the nature of the dependency scenarios and its practicality for industrial practitioners, rather than only reusing the conventional available metrics stated in previous literature. Note that interdependency-related criticality and the degree of dependency are mentioned within the theoretical literature as the two main ways of expressing metrics for infrastructure dependency. Such classification could be appropriate for an economic-based interdependency analysis which mainly focuses on a very limited number of elements for each infrastructure system (e.g. input, output and supply and demand related indices). However, it would be very difficult to classify engineering metrics when dealing with various technical interdependencies at a large scale, where many scenarios occur. Therefore, it is essential to focus on either one or very few scenarios at a time within the scope of an interdependency-related problem when aiming to produce useful metrics.

Regarding future research, in addition to specific recommendations provided in previous chapters (Chapter 4 and Chapter 5), it is recommended that the academic knowledge of dependencies of railways and other infrastructure systems need to be expanded in all dimensions (e.g. physical, cyber, logical) and to be completed from all perspectives (conceptual, economic, vulnerability and data management). This is because very little academic knowledge is documented or available even at a very high-level conceptual stage that explains how railways connect to other infrastructure systems. It is worth mentioning that it is clearly impossible to effectively examine or understand the performance and behaviour of any given infrastructure regarding the future challenges in isolation from the environment or other infrastructures. Climate change, demographic change and interoperability and digitalisation all pose as a challenge for the railways and calls for a collaborative effort to improve the knowledge of railway dependencies beyond its traditional boundaries.

Moreover, it is worthwhile mentioning that a system-of-system approach towards investigating interdependencies is encouraged in this research. Disruptions, vulnerabilities and failures need to be understood and quantified, not only from the viewpoint of the operations of a single sector/infrastructure, but also from the perspective of their ultimate purpose. In such contexts, the railway as a sub-system of transport systems needs to not only operate normally, but also needs to support passengers to make a successful complete start-end journey. In certain scenarios, such as extreme weather conditions, a cancelled train service which protects customers from moving themselves and their commodities to heavily disrupted areas should not be deemed as a failure. Again, this emphasizes the major role of scenario development while investigating infrastructure dependencies in a pragmatic manner.

To summarise, the interdependency investigation using a participatory-based approach can be viewed as a targeted deployment, whereby poorly known local and engineering dependencies will be identified and prioritised according to the most compelling cases that have high impacts on the operation of systems. The conclusive argument of this research for investigating dependencies between sectors, is that academic researchers are required in some cases to step back from a scientific approach (e.g. system engineering, mathematical, analytical and numerical, as well as experimental approaches) and instead adopt a participatory approach as an initial step. Researchers can later evaluate the outcome of participatory modelling using conventional numerical and experimental approaches or system engineering tools depending on the nature of the (inter)dependency under investigation.

The participatory modelling which formed the basis of this research seems to be a totally absent step from most academic research related to infrastructure dependency. This research argued and demonstrated that an approach such as this could be necessary when investigating some dependencies, and at least be complimentary when investigating many others, and could be considered to have successfully contributed to academic knowledge in this area. The infrastructure managers and other key stakeholders who support interdependency research studies can later appreciate their dependence on upstream critical infrastructures and make contingency plans or design changes by using the output of studies similar to this research project.

Chapter 7 Conclusions

7.1 Summary of the thesis

Railways as complex systems have many dependencies. Assets, resources and materials within the system are dependent on other assets, resources, materials or conditions inside and outside of the railway system. In this thesis some railway-related dependencies with other infrastructure systems have been studied by using a participatory-based approach as a key and beneficial method. The existing literature in the subject of infrastructure dependency as well as participatory-based modelling has been thoroughly and critically reviewed and it has been found that the interdependencies at a sector level and a technical environment have not received enough attention. It has also been found that the methods and approaches for exploration are limited to the conventional and common ones outlined in infrastructure-dependency related literature. However, these are not necessarily suitable for the investigation of little-known scenario-specific engineering dependencies.

This thesis introduced the application of a participatory-based approach for the investigation of technical dependencies of railways and other infrastructure systems. Entities or elements included in such approaches have been explained and their implications for the advancement the study area, and practical implications for the industry were discussed. In this thesis two little-known scenarios of dependencies related to railways have been investigated. In the first scenario the dependency that exists between electricity generation (power output) and freight railway traffic was investigated. The purpose of the investigation in the second scenario was to evaluate the dependency that exists between railways and urban water distribution systems in the event of track flooding caused by a water main burst. In the course of these studies, time series analysis for explaining the behaviour of dependencies in time has been employed and a novel modelling and simulation technique has been developed and used to quantify the dependencies which have been highlighted qualitatively as scenarios. Unlike in the previous research in this field, in which usually the availability of the simulation tool dictates the interdependency analysis, the model and simulation techniques used for this work have been developed based on the requirements of the different scenarios through consultation of industrial practitioners. Interviews, meetings and workshops were extensively used throughout different stages of this research to identify dependency scenarios, collect data and input for modelling and simulation and incorporating feedbacks into the qualitative findings. For the first scenario, different statistical and time-series analysis has been carried out whereas in the second scenario both a hydraulic (physics-based modelling) and numerical simulations have been developed.

7.2 Main findings and research contributions

From reviewing literature, the stakeholder engagement, the scenario analysis and case study and the modelling in this thesis, the following conclusions can be drawn:

- Considering the convergent future challenges such as climate change and demographic changes, we can no longer wait until failures reveal the dependencies that exist between infrastructures/sectors. Many studies investigated interdependencies between infrastructures using different dimensions (e.g. national vs local) and approaches (e.g. empirical approach vs predictive approach) that can act complementarily. Different modelling and simulation tools which analyse the interdependencies from different viewpoints are necessary for a comprehensive understanding of this topic.
- The existing knowledge of infrastructure dependencies is limited in many aspects including the common approaches, methods and models, the types of well-known dependencies across infrastructures, the available metrics to quantify dependencies and the existing insight regarding sector-specific engineering and local level dependencies.
- Engagement with experts and using the best knowledge regarding infrastructures that is available to those who own, operate and manage them is absent from the academic literature within the area of infrastructure dependency.
- Modelling and analysis of complex systems and in particular modelling and analysis of interdependencies between different infrastructure systems present great challenges and the knowledge in this field is still in its early stages. First, many low likelihood dependencies may only be illuminated by failure of the

systems, and therefore infrastructure owners neglect them. Furthermore, the nature of some dependencies between technical infrastructures cannot be captured by common macroscopic (economic) or conceptual indices or metrics and hence introducing new relevant metrics are required. Also, in many cases no tool exists to dynamically model the identified disruptions.

- In the first place less evident dependencies that may appear as cross-sectoral risks should be identified by studying past examples and stakeholder engagement. Later, relevant metrics need to be defined in order to properly relate two infrastructures throughout the recognised scenario. Taking into consideration the concerns and motivations of relevant stakeholders, modelling and simulation tools should be developed to provide further knowledge about the particular dependency.
- In many cases, interdependent risks at operational level could have been neglected and hence not well investigated due to one (or all) of the following:
  - Infrastructure sectors would have different identification and prioritizations of risks according to their particular goals and remits. Hence stakeholders have different concerns. Academic researchers can play a major role in managing the evaluation of scenarios across sectors and their traditional boundaries.
  - Relevant asset data could be lost, incomplete or insufficient (especially in highly complex old systems). Efforts need to be made to collect these data for a particular dependency scenario. For time-dependent scenarios data needs to be collected that covers a long time period, whereas, for other scenarios, data might need to be collected over a large spatial extent. Furthermore, new initiatives are needed to collect, refine and make accessible national scale datasets that can support the investigation of technical scenarios regarding dependencies for railways and other infrastructure systems.
  - The impacts on one (or more) of the systems can be indirect (e.g. the operation of the systems itself is not disturbed). On the other hand, although the scenario can have a significant impact (consequence) on systems, its likelihood would usually be low. Hence, academic research needs to contribute to demonstrating the significance of a system-of-system resilience for infrastructure systems.

    - The origin and the flow of failures within interdependent infrastructures may not be visible or reported. That is why reporting symptoms and documenting them by industrial practitioners is important. Also, a systemic mechanism would be required to collect the details of potential but non-evident failure scenarios for a system such as railways at a technical environment.
- The subject of infrastructure interdependency is very complicated due to the nature of complex adaptive systems (critical infrastructures). In order to tackle the subject, a significant number of assumptions and simplifications need to be made. For instance, the less critical assets for a particular scenario under investigation need be ignored. This is specifically important when investigating a sector such as railways, which due to its diversity and variability, is involved in numerous poorly known dependency scenarios.
- Details related to interdependency scenarios are numerous and hence experts' judgement and participatory modelling are necessary in order to capture details before predictive approaches and relevant models are employed to quantify the cross-sectoral scenario/ interaction. Eliminating the knowledge of experts at any stage of infrastructures dependency research reduces its positive impact and increases the chance of including wrong assumptions.
- Railways and other interdependent sectors require improvement in communication, data sharing mechanisms, asset inventory and quantified analyses of shared risks in order to understand poorly known dependencies that exist. This would pave the road for holistic approaches towards managing infrastructure systems as a resilient system of systems.
- The dependency of electricity power production on railway freight traffic has been investigated in chapter 4 using actual and quantitative data from a power plant and the supply of fuel by freight traffic. Statistical and time series analysis have been used to analyse the data. From this case study, it concluded the following:
    - The descriptive statistics showed how the weekly, monthly, daily and weekday-based data of railway traffic and electricity production varies. The results showed that the biomass commodity movement is less irregular than the coal commodity movement, while the electricity

generation at power stations follows the same variable pattern of national electricity generation.

  - The autocorrelation showed how the supply and production behave in time and whether they have similar trend or not. The Pearson correlation showed whether there is any direct correlation between the supply and the production without looking at the behaviour in time. Both methods give the same conclusion that there is no tight dependency between coal supply and power production. For the Biomass supply, there is a clear similarity between the two autocorrelation curves showing a strong dependency between them. When directly calculating the correlation between the supply and the energy production using the Pearson correlation method, the same behaviour has been noted.
  - The ARIMA modelling showed that it is possible to forecast future values of biomass commodity movement and biomass-fuelled electricity generation based on the past values by considering an autoregressive moving average behaviour in time for these datasets.
  - The stock level at the electricity power stations showed that most of the biomass stock might be used within roughly a week after its arrival.
  - Evaluation of vulnerability to shortage due to the complexity of supply of perishable commodity by rail could show that currently Drax would be able to safely operate about only 6 days (and not further) during railway disruptions.
  - It has been recognized that the results of this dependency are based on only one case study for a single power plant and on the available data at the time of this study. In order to generalise the results and conclusion, more similar case studies could be used. The work of this thesis gives the basis for such data analysis.
- A novel numerical model based on the conservation of mass has been developed and validated using experimental data on a small scale in chapter 5. The model is used to evaluate the scenario of track flooding caused by a water main burst and quantify the dependency of the operation of a railway system on such flooding. The developed model has been used to facilitate characterisation of a specific dependency that exists between two

infrastructure systems, namely an urban railway and trunk main network at operation environment. A sensitivity analysis of the different parameters that affect flooding in a railway system has been made and it was found that:

  - The higher the water flow at the burst, the longer the time for burst-induced track flooding.
  - The newer the ballast of the track (higher porosity), the longer the time for burst-induced track flooding.
  - The greater the drainage capacity along the track the longer the time for burst-induced track flooding. However, if the flow rate is high the effect of local drainage on track flooding is negligible.
  - For a small burst discharge, the time for burst-induced track flooding increases when the distance between the burst and the lowest point increases. However, for a high burst discharge, the effect of distance is negligible.
  - The steeper the track, the shorter the time for burst-induced track flooding. However, there is no change in the results if the track slope is more than 1/113.

As for the findings of both case studies as well as the overall research and its approach, recommendations regarding further research have been made in the thesis. However, the next section includes several general areas for future researchers to focus on.

7.3 Future research

It is concluded that the proposed research gives a valuable foundation to proactive decision-making regarding railway infrastructure risks and vulnerabilities.

There are a number of areas worthy of further research in the very important subject of infrastructure dependencies. The potential future research is listed as follows:

- In general, it is necessary to develop relevant, reliable, consistent and detailed temporal and spatial databases that facilitate investigation of dependencies. The effort by University College London to develop a data system to present the real-time movements of intermodal freight is a good example of such databases. Such databases are essential to quantify the dependencies and hence inform any long-term and future decision making. They are also useful for the calibration of existing models and simulation tools available.

- Further focused research is needed to find potential solutions for removing traditional boundaries between infrastructure systems and encouraging cross-sectoral thinking among industrial practitioners. Barriers in communication, issues around system management, problems in asset inventory and a lack of data sharing mechanisms need to be identified for infrastructures and sectors. Appropriate solutions to remove obstacles need to be identified and evaluated.
- The analysis presented in chapter 4 and the proposed model in chapter 5 should be viewed as a first step in an attempt to develop a more comprehensive risk assessment and management framework for ensuring the integrity and continued operability of complex critical and technical infrastructures. More sector/infrastructure specific and scenario-based approaches and models are needed to investigate dependencies at a technical environment.

Reference

1. ABP. (2012). Port of Immingham Master Plan 2010-2030.
2. ABP. (2018). More about Immingham. Available at: http://www.abports.co.uk/Our_Locations/Humber/Immingham/More_about_Immingham/
3. Allen, J., Browne, M., Hunter, A., Boyd, J., & Palmer, H. (1998). Logistics management and costs of biomass fuel supply. International Journal of Physical Distribution & Logistics Management, 28(6), 463-477.

4. Amin, M. (2004). North American electricity infrastructure: System security, quality, reliability, availability, and efficiency challenges and their societal impacts.

5. Apostolakis, G. E., & Lemon, D. M. (2005). A screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism. Risk Analysis, 25(2), 361-376.

6. Arkell, B. and Darch, G. (2006). Impact of climate change on London's transport network. Proc. Inst. Civ. Eng., Municip. Eng., 159, 231–23722.

7. ARR. (2010). Association of American Railroads. Coal: Freight Rail Powers the Nation. Available at: https://www.aar.org/article/freight-rail-coal/
8. Baker, C. J., Chapman, L., Quinn, A., & Dobney, K. (2010). Climate change and the railway industry: a review. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *224*(3), 519-528.
9. Bale, C. (2018). Participatory modelling: A review of applications in energy whole-systems modelling to support decision making.
10. Barr, S., Alderston, D., Robson, C., Otto, A., Hall, J., Thacker, S., & Pant, R. (2013). A national scale infrastructure database and modelling environment for the UK.

11. Barton, D. C., & Stamber, K. L. (2000). An agent-based microsimulation of critical infrastructure systems (No. SAND2000-0808C). Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US).
12. Barton, D. C., Eidson, E. D., Schoenwald, D. A., Stamber, K. L., & Reinert, R. K. (2000). Aspen-EE: an agent-based model of infrastructure interdependency. SAND2000-2925. Albuquerque, NM: Sandia National Laboratories.
13. Baruah, P. Chaudry, M. Qadrdan, M. Eyre, N and Jenkins, N. (Eds.). (2016). Energy Systems Assessment. The future of national infrastructure: A system-of-systems approach. Cambridge University Press.
14. Basco-Carrera, L., Mendoza, G. (2017). Collaborative Modelling. Engaging Stakeholders in Solving Complex Problems of Water Management. Global Water Partnership Perspectives Paper No. 10.
15. BBC. (2012). Immingham port's first public open day marks 100 years. Available at: https://www.bbc.co.uk/news/uk-england-humber-18944067
16. BBC., (2012) available at: http://www.bbc.co.uk/news/uk-england-london-18345503
17. Benn, J. (2013). Railway bridge failure during flooding in the UK and Ireland. *Proceedings of the Institution of Civil Engineers-Forensic Engineering*, *166*(4), 163-170.
18. Binti Sa'adin, S. L., Kaewunruen, S., & Jaroszweski, D. (2016). Heavy rainfall and flood vulnerability of Singapore-Malaysia high speed rail system. Australian Journal of Civil Engineering, 14(2), 123-131.
19. Biomass Energy Centre (2011), information available at http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17306&_dad=portal
20. Blainey, S. P. and Preston, J. M. (Eds.). (2016). Transport systems assessment. The future of national infrastructure: A system-of-systems approach. Cambridge University Press.
21. Blum, J., & Eskandarian, A. (2002). Enhancing intelligent agent collaboration for flow optimization of railroad traffic. Transportation Research Part A: Policy and Practice, 36(10), 919-930.

22. Boxall, J. B., O'Hagan, A., Pooladsaz, S., Saul, A. J., & Unwin, D. M. (2007). Estimation of burst rates in water distribution mains. In *Proceedings of the Institution of Civil Engineers-Water Management* (Vol. 160, No. 2, pp. 73-82). London:[Published for the Institution of Civil Engineers by Thomas Telford Ltd.], c2004-.

23. British Steel. (2017). Rail, flat-bottomed vignole rail. Dimensions and properties.

24. Brown, T., Beyeler, W., & Barton, D. (2004). Assessing infrastructure interdependencies: the challenge of risk analysis for complex adaptive systems. *International Journal of Critical Infrastructures*, *1*(1), 108-117.

25. BS EN. (2017). 50126-1. Railway applications. The specification and demonstration of reliability, availability, maintainability and safety (RAMS). Generic RAMS process.

26. Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. *Nature*, *464*(7291), 1025-1028.

27. Burgess, J., Stirling, A., Clark, J., Davies, G., Eames, M., Staley, K., & Williamson, S. (2007). Deliberative mapping: a novel analytic-deliberative methodology to support contested science-policy decisions. Public Understanding of Science, 16(3), 299-322.

28. Butts, J., & Shenoi, S. (Eds.). (2011). Critical Infrastructure Protection V: 5th IFIP WG 11.10 International Conference on Critical Infrastructure Protection, ICCIP 2011, Hanover, NH, USA, March 23-25, 2011, Revised Selected Papers (Vol. 367). Springer.

29. Calvillo, C. F., Sánchez-Miralles, A., & Villar, J. (2016). Energy management and planning in smart cities. *Renewable and Sustainable Energy Reviews*, *55*, 273-287.

30. Carreras, B. A., Newman, D. E., & Dobson, I. (2012). Determining the vulnerabilities of the power transmission system. In System Science (HICSS), 2012 45th Hawaii International Conference on (pp. 2044-2053). IEEE.

31. Casalicchio, E., & Galli, E. (2008, March). Metrics for quantifying interdependencies. In International Conference on Critical Infrastructure Protection (pp. 215-227). Springer, Boston, MA.
32. Casalicchio, E., Galli, E., & Tucci, S. (2007). Federated agent-based modeling and simulation approach to study interdependencies in IT critical infrastructures. In Proceedings of the 11th IEEE International Symposium on Distributed Simulation and Real-Time Applications (pp. 182-189). IEEE Computer Society.
33. Chang, S. E., McDaniels, T. L., Mikawoz, J., & Peterson, K. (2007). Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. Natural Hazards, 41(2), 337-358.
34. Chen, P., Scown, C., Matthews, H. S., Garrett Jr, J. H., & Hendrickson, C. (2009). Managing critical infrastructure interdependence through economic input-output methods. Journal of Infrastructure systems, 15(3), 200-210.
35. Chopra, S., and M. S. Sodhi. 2004. "Managing Risk to Avoid Supply-chain Breakdown." MIT Sloan Management Review 46: 53–62.
36. Chou, C. C., & Tseng, S. M. (2010). Collection and analysis of critical infrastructure interdependency relationships. Journal of computing in civil engineering, 24(6), 539-547.
37. Chow, V. T., 1959, Open-channel hydraulics: New York, McGraw-Hill Book Co., 680 p.
38. Climate UK (2012) Your Climate- the Climate Change Partnership for Yorkshire & Humber, available at www.yourclimate.org/
39. Connor. (2017). Basic Railway Signalling. Railway Technical Website. Infopaper No. 6. One of a series of papers on technical issues published by the RTW from time to time. 7th May 2017.
40. Cooper, N. R., Blakey, G., Sherwin, C., Ta, T., Whiter, J. T., & Woodward, C. A. (2000). The use of GIS to develop a probability-based trunk mains burst risk model. Urban Water, 2(2), 97-103.
41. CPNI. (2018). Centre for the Protection of National Infrastructure. Critical National infrastructure. Available at https://www.cpni.gov.uk/critical-national-infrastructure-0
42. CST. (2009). A national infrastructure for the 21st century. London, UK, Council for Science and Technology.

43. Cuttill, P. (2017). Thames Water trunk mains forensic review. Final findings report. Thames Water.

44. Davesrailpics. (2014). Derailment at Brocklesby Junction.15th July 2014. Available at: http://www.davesrailpics.bravehost.com/brockderail/brockderail.htm

45. Defra. (2015). Manual on Treatment for Small Water Supply Systems. Updated Report. June 2015.

46. Department for Energy and Climate Change (DECC). (2013) Updated energy and emissions projections

47. Department for Energy and Climate Change (DECC). (2015) Coal statistics and Digest of UK Energy Statistics (DUKES)

48. Department for Energy and Climate Change (DECC). (2016). Life cycle impact of biomass electricity in 2020. Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK.

49. Department for Transport. (2014) Transport Resilience Review: A review of the resilience of the transport network to extreme weather events.

50. DfT. (2018a). UK Port Freight Statistics: 2017. Statistical Release. National Statistics. 22 August 2018.

51. DfT. (2018b). Transport Statistics Great Britain 2018 Moving Britain Ahead. Department for Transport. National Statistics.

52. Drax (2015). Biomass supply, available at: www.drax.com

53. Dueñas-Osorio, L., & Kwasinski, A. (2012). Quantification of lifeline system interdependencies after the 27 February 2010 Mw 8.8 offshore Maule, Chile, earthquake. Earthquake Spectra, 28(S1), S581-S603.

54. Dunn, S., & Wilkinson, S. M. (2012). Identifying critical components in infrastructure networks using network topology. Journal of Infrastructure Systems, 19(2), 157-165.

55. EN Standards. (2006). COMMUNICATION FROM THE COMMISSION on a European Programme for Critical Infrastructure Protection. Brussels, 12.12.2006 COM (2006) 786 final.

56. Energy UK. (2018). The energy market explained. Available at: https://www.energy-uk.org.uk/energy-industry/the-energy-market.html
57. Environment Agency. (2014). The Tidal Surge on the 5th of December and its Effects on the Humber. Environment Agency November 2014.
58. Environment Agency. (2015) available at: https://data.gov.uk/dataset/risk-of-flooding-from-rivers-and-sea .
59. Esveld, C. (2001). Modern Railway Track, 2nd Editon. Delft university of Technology.
60. European Commission. (2018). Integrated Transport: Enhancing the End to End Journey. Available at: https://trimis.ec.europa.eu/programme/integrated-transport-enhancing-end-end-journey#tab-projects
61. Eusgeld, I., Henzi, D., & Kröger, W. (2008). Comparative evaluation of modeling and simulation techniques for interdependent critical infrastructures. Scientific Report, Laboratory for Safety Analysis, ETH Zurich, 6-8.
62. Evening Standard. (2015) available at: http://www.standard.co.uk/news/london/commuter-misery-at-farringdon-continues-after-tunnel-flood-despite-rail-bosses-claiming-normal-10006397.html
63. Ezell, B. C., Farr, J. V., & Wiese, I. (2000). Infrastructure risk analysis model. Journal of infrastructure systems, 6(3), 114-117.
64. Ezell, B. C., Farr, J. V., & Wiese, I. (2000). Infrastructure risk analysis of municipal water distribution system. Journal of Infrastructure Systems, 6(3), 118-122.
65. Faturechi, R., & Miller-Hooks, E. (2014). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. Journal of infrastructure systems, 21(1), 04014025.
66. Fernandez, S. J., Shankar, M., Nutaro, J. J., Liu, Y., Dimitrovski, A. D., Omitaomu, O. A., Christopher S. GroerKyle L. SpaffordRanga R. & Vatsavai, R. R. (2013). Real-time simulation of power grid disruption. U.S. Patent Application No 13/747,779
67. Franchina, L., Carbonelli, M., Gratta, L., Crisci, M., & Perucchini, D. (2011). An impact-based approach for the analysis of cascading effects in critical infrastructures. International journal of critical infrastructures, 7(1), 73-90.

68. Francis, R., & Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, *121*, 90-103. Setola, R., De Porcellinis, S., & Sforna, M. (2009). Critical infrastructure dependency assessment using the input–output inoperability model. *International Journal of Critical Infrastructure Protection*, *2*(4), 170-178.

69. French, J., Mawdsley, R., Fujiyama, T., & Achuthan, K. (2017). Combining machine learning with computational hydrodynamics for prediction of tidal surge inundation at estuarine ports. Procedia IUTAM, 25, 28-35.

70. Friedl, F., Möderl, M., Rauch, W., Liu, Q., Schrotter, S., & Fuchs-Hanusch, D. (2012). Failure propagation for large-diameter transmission water mains using dynamic failure risk index. In *World Environmental and Water Resources Congress 2012: Crossing Boundaries* (pp. 3082-3095).

71. Gallegos, H. A., Schubert, J. E., & Sanders, B. F. (2009). Two-dimensional, high-resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California. *Advances in water resources*, *32*(8), 1323-1335.

72. Gambardella, L. M., Rizzoli, A. E., & Funk, P. (2002). Agent-based planning and simulation of combined rail/road transport. Simulation, 78(5), 293-303.

73. Gao, J., Buldyrev, S. V., Stanley, H. E., & Havlin, S. (2012). Networks formed from interdependent networks. *Nature physics*, *8*(1), 40.

74. Gedik, R., Medal, H., Rainwater, C., Pohl, E. A., & Mason, S. J. (2014). Vulnerability assessment and re-routing of freight trains under disruptions: A coal supply chain network application. *Transportation Research Part E: Logistics and Transportation Review*, *71*, 45-57.

75. Ghataora, G., & Rushton, K. (2012). Movement of Water Through Ballast and Subballast for Dual-Line Railway Track. *Transportation Research Record: Journal of the Transportation Research Board*, (2289), 78-86.

76. González-Gil, A., Palacin, R., Batty, P., & Powell, J. P. (2014). A systems approach to reduce urban rail energy consumption. *Energy Conversion and Management*, *80*, 509-524.

77. Google Maps. (2018). Google Maps [Online]. Available at: https://www.google.com/maps

78. Gursesli, O., & Desrochers, A. A. (2003). Modeling infrastructure interdependencies using Petri nets. In Systems, Man and Cybernetics, 2003. IEEE International Conference on (Vol. 2, pp. 1506-1512). IEEE.

79. Haimes, Y. Y., & Jiang, P. (2001). Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure systems*, *7*(1), 1-12.

80. Haimes, Y. Y., Horowitz, B. M., Lambert, J. H., Santos, J. R., Lian, C., & Crowther, K. G. (2005). Inoperability input-output model for interdependent infrastructure sectors. I: Theory and methodology. Journal of Infrastructure Systems, 11(2), 67-79.

81. Haimes, Y. Y., Horowitz, B. M., Lambert, J. H., Santos, J., Crowther, K., & Lian, C. (2005). Inoperability input-output model for interdependent infrastructure sectors. II: Case studies. *Journal of Infrastructure Systems*, *11*(2), 80-92.

82. Hall, J. W., Tran, M., Hickford, A. J., & Nicholls, R. J. (Eds.). (2016). The future of national infrastructure: A system-of-systems approach. Cambridge University Press.

83. Hall, J., Henriques, J., Hickford, A., & Nicholls, R. (2012). A Fast Track Analysis of strategies for infrastructure provision in Great Britain: Technical report.

84. Hall, J.W., Henriques, J.J., Hickford, A.J., Nicholls, R.J., Baruah, P., Birkin, M., Chaudry, M., Curtis, T.P., Eyre, N., Jones, C. and Kilsby, C.G. (2014). Assessing the long-term performance of cross-sectoral strategies for national infrastructure. Journal of Infrastructure Systems, 20(3), p.04014014.

85. Hallegatte, S. (2008). An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina. Risk Analysis: An International Journal, 28(3), 779-799.

86. Han, J., & Hayashi, Y. (2008). A system dynamics model of CO2 mitigation in China's inter-city passenger transport. Transportation Research Part D: Transport and Environment, 13(5), 298-305.
87. Hare, M., Letcher, R. A., & Jakeman, A. J. (2003). Participatory modelling in natural resource management: a comparison of four case studies. Integrated Assessment, 4(2), 62-72.

88. Hasnayn, M. M., Medero, G. M., & Woodward, P. K. (2015). Railway track performance during and post flooding.

89. Heyns, F. J. (2000). Railway track drainage design techniques.

90. Ho, W., Zheng, T., Yildiz, H., & Talluri, S. (2015). Supply chain risk management: a literature review. International Journal of Production Research, 53(16), 5031-5069.
91. Homeland Security. (2018). U.S. Department of Homeland Security. Critical Infrastructure Sectors. Available at https://www.dhs.gov/cisa/critical-infrastructure-sectors
92. House of Commons. (2011). Transport and the economy. Third Report of Session 2010–11 Volume I Report, together with formal minutes, oral and written evidence.

93. Hunter, N. M., Bates, P. D., Neelz, S., Pender, G., Villanueva, I., Wright, N. G. & Crossley, A. J. (2008). Benchmarking 2D hydraulic models for urban flood simulations. In *Proceedings of the institution of civil engineers: water management* (Vol. 161, No. 1, pp. 13-30). Thomas Telford (ICE publishing).

94. Ibáñez, E., McCalley, J., Aliprantis, D., Brown, R., Gkritza, K., Somani, A., & Wang, L. (2008). National energy and transportation systems: Interdependencies within a long term planning model. In Energy 2030 Conference, 2008. ENERGY 2008. IEEE (pp. 1-8). IEEE.

95. Indraratna B, Khabbaz H, Salim W, Christie D. (2006). Geotechnical properties of ballast and the role of geosynthetics. Institution of Civil Engineers.

96. Jaroszweski, D. (2012). Chapter 6 The Impacts of Climate Change on the National Freight Sector. In Transport and climate change (pp. 137-173). Emerald Group Publishing Limited.
97. Jaroszweski, D., Hooper, E., & Chapman, L. (2014). The impact of climate change on urban transport resilience in a changing world. Progress in Physical Geography, 38(4), 448-463.
98. Jaroszweski, D., Hooper, E., Baker, C., Chapman, L., & Quinn, A. (2015). The impacts of the 28 June 2012 storms on UK road and rail transport. Meteorological Applications, 22(3), 470-476.
99. Jesson, D., Farrow, J., Mulheron, M., Nensi, T., & Smith, P. (2017). Achieving Zero Leakage by 2050: Basic Mechanisms of Bursts and Leakage.
100. Johansson, J. (2010). Risk and vulnerability analysis of interdependent technical infrastructures. PhD avhandling, Universitetet i Lund.
101. Johansson, J., & Hassel, H. (2010). An approach for modelling interdependent infrastructures in the context of vulnerability analysis. Reliability Engineering & System Safety, 95(12), 1335-1344.
102. Johansson, J., Hassel, H., & Cedergren, A. (2011). Vulnerability analysis of interdependent critical infrastructures: case study of the Swedish railway system. International journal of critical infrastructures, 7(4), 289-316.
103. Johansson, J., Hassel, H., & Zio, E. (2013). Reliability and vulnerability analyses of critical infrastructures: comparing two approaches in the context of power systems. Reliability Engineering & System Safety, 120, 27-38.
104. Johansson, J., Jonsson, H., & Johansson, H. (2007). Analysing the vulnerability of electric distribution systems: a step towards incorporating the societal consequences of disruptions. International Journal of Emergency Management, 4(1), 4-17.
105. Jönsson, H., Johansson, J., & Johansson, H. (2008). Identifying critical components in technical infrastructure networks. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 222(2), 235-243.

106. Kajitani, Y., & Sagai, S. (2009). Modelling the interdependencies of critical infrastructures during natural disasters: a case of supply, communication and transportation infrastructures. International journal of critical infrastructures, 5(1-2), 38-50.

107. Karush, W. (1957). A queuing model for an inventory problem. Operations research, 5(5), 693-703.

108. Kellermann, P., Schöbel, A., Kundela, G., & Thieken, A. H. (2015). Estimating flood damage to railway infrastructure–the case study of the March River flood in 2006 at the Austrian Northern Railway. *Natural Hazards and Earth System Sciences*, *15*(11), 2485.

109. Kellermann, P., Schönberger, C., & Thieken, A. H. (2016). Large-scale application of the flood damage model RAilway Infrastructure Loss (RAIL). *Natural Hazards and Earth System Sciences*, *16*(11), 2357.

110. Kelly, S. (2015). Estimating economic loss from cascading infrastructure failure: a perspective on modelling interdependency. Infrastructure Complexity, 2(1), 1-13.

111. Kjølle, G. H., Utne, I. B., & Gjerde, O. (2012). Risk analysis of critical infrastructures emphasizing electricity supply and interdependencies. Reliability Engineering & System Safety, 105, 80-89.

112. Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. Transportation Research Part D: Transport and Environment, 14(3), 205-221.

113. Kopylec, J., D'Amico, A., & Goodall, J. (2007, March). Visualizing cascading failures in critical cyber infrastructures. In International Conference on Critical Infrastructure Protection (pp. 351-364). Springer, Boston, MA.

114. Kotzanikolaou, P., Theoharidou, M., & Gritzalis, D. (2013). Cascading effects of common-cause failures in critical infrastructures. In International Conference on Critical Infrastructure Protection (pp. 171-182). Springer, Berlin, Heidelberg.

115. Krueger, T., Page, T., Hubacek, K., Smith, L., & Hiscock, K. (2012). The role of expert opinion in environmental modelling. Environmental Modelling & Software, 36, 4-18.

116. Landström, C., Whatmore, S. J., Lane, S. N., Odoni, N. A., Ward, N., & Bradley, S. (2011). Coproducing flood risk knowledge: redistributing expertise in critical ‘participatory modelling’. Environment and Planning A, 43(7), 1617-1633.

117. Larsson, S., & Ek, E. (2004, June). The black-out in southern Sweden and eastern Denmark, September 23, 2003. In IEEE Power Engineering Society General Meeting, 2004. (pp. 1668-1672). IEEE.

118. Lau, H. S. (1997). Simple formulas for the expected costs in the newsboy problem: An educational note. European Journal of Operational Research, 100(3), 557-561.

119. Leandro, J., Chen, A. S., Djordjević, S., & Savić, D. A. (2009). Comparison of 1D/1D and 1D/2D coupled (sewer/surface) hydraulic models for urban flood simulation. *Journal of hydraulic engineering*, *135*(6), 495-504.

120. Lee II, E. E., Mitchell, J. E., & 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), 1303-1317.

121. Lian, C., & Haimes, Y. Y. (2006). Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input–output model. Systems Engineering, 9(3), 241-258.

122. Limerinos, J. T. 1970. ‘Determination of the Mannings coefficient from measured bed roughness in natural channels’, US Geol. Surv. Wat. Supply Pap., 1898-B, 47 pp.

123. Lindahl, M. (2001). Track geometry for high-speed railways. TRITA-FKT Report, 54.

124. Little, R. G. (2002). Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures. Journal of Urban Technology, 9(1), 109-123.

125. López-Ibáñez, M. (2009). Operational optimisation of water distribution networks (Doctoral dissertation, Edinburgh Napier University).

126. Lovrić, M., Blainey, S., & Preston, J. (2017). A conceptual design for a national transport model with cross-sectoral interdependencies. Transportation Research Procedia, 27, 720-727.

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

128. Makar, J. M., Desnoyers, R., & McDonald, S. E. (2001). Failure modes and mechanisms in gray cast iron pipe. Underground Infrastructure Research, 1-10.

129. Manning, L. J., Graham, D. W. and Hall, J. W. (Eds.). (2016). Chapter 7 Wastewater systems assessment. The future of national infrastructure: A system-of-systems approach. Cambridge University Press.

130. Mark, O., Weesakul, S., Apirumanekul, C., Aroonnet, S. B., & Djordjević, S. (2004). Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology*, *299*(3-4), 284-299.

131. McDaniels, T., Chang, S., Cole, D., Mikawoz, J., & Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. Global Environmental Change, 18(2), 310-318.

132. McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., & Reed, D. (2007). Empirical framework for characterizing infrastructure failure interdependencies. *Journal of Infrastructure Systems*, *13*(3), 175-184.

133. MDS Transmodal. The potential impact of increases in track access charges on the transport by rail of biomass by MDS Transmodal for the Office of Rail and Road ORR/ST/17-88. April 2018 Ref: 218010r7.

134. Mendonça, D., & Wallace, W. A. (2006). Impacts of the 2001 world trade center attack on New York city critical infrastructures. Journal of Infrastructure Systems, 12(4), 260-270.

135. Miller, R. E., & Blair, P. D. (2009). Input-output analysis: foundations and extensions. Cambridge university press.

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

137. Moran, A. P., Thieken, A. H., Schöbel, A., & Rachoy, C. (2010). Documentation of flood damage on railway infrastructure. In *Data and Mobility* (pp. 61-70). Springer, Berlin, Heidelberg.

138. Nagurney, A., & Qiang, Q. (2008). A network efficiency measure with application to critical infrastructure networks. Journal of Global Optimization, 40(1-3), 261-275.

139. National Statistics. (2017). DIGEST OF UNITED KINGDOM ENERGY STATISTICS (DUKES) 2017. Department for business, energy and industrial strategy.

140. National Statistics. (2018). UK Energy Brief 2018. Department for Business, Energy and Industrial Strategy.

141. Network Rail. (2009). Culvert detailed examination report. Amey 19 May 2009.

142. Network Rail. (2010). Railway Drainage Systems Manual. Part 2B: Hydraulic design of new Drainage Systems.

143. Network Rail. (2012). CP5 Drainage Asset Policy 2012 Update rev 28 FINAL 2012_12_18

144. Network Rail. (2013). Long Term Planning Process: Freight Market Study

145. Network Rail. (2016). Safety Central: TRUST. Available at: https://safety.networkrail.co.uk/jargon-buster/trust/

146. Network Rail. (2017). The risk of bridge strikes. Bridge strikes continue to be a significant risk to railway safety. archived as of 9th January 2017.
147. Network Rail. (2018). Rail is vital to economic growth. Available at: https://www.networkrail.co.uk/who-we-are/jobs-and-growth/
148. Network Rail. Railway drainage systems manual. (2011).
149. North East Lincolnshire Council (2010) Strategic Flood Risk Assessment 2010 (SFRA), available at http://www.nelincs.gov.uk/
150. North, M. J., Collier, N. T., Ozik, J., Tatara, E. R., Macal, C. M., Bragen, M., & Sydelko, P. (2013). Complex adaptive systems modeling with Repast Simphony. Complex adaptive systems modeling, 1(1), 3.
151. Oliva, G., Panzieri, S., & Setola, R. (2010). Agent-based input–output interdependency model. International Journal of Critical Infrastructure Protection, 3(2), 76-82.
152. ORR, Office of Rail and Road. (2017). Freight rail usage 2017-18 Q1 statistical release. National statistics.

153. ORR. (2008). Comparison of North American Rail Asset Life Report. Office of Rail Regulation. Document ORR/RP/442/NATSLC FINAL. Arup.

154. ORR. (2018). Freight Rail Usage 2017-18 Q4 Statistical Release. Office of Rail and Road. National Statistics. Publication date: 7 June 2018. Available at: http://www.orr.gov.uk/statistics/published-stats/statistical-releases
155. Otto, A., Hall, J. W., Hickford, A. J., Nicholls, R. J., Alderson, D., Barr, S., & Tran, M. (2016). A quantified system-of-systems modeling framework for robust national infrastructure planning. IEEE Systems Journal, 10(2), 385-396.
156. Oughton, E. J., Usher, W., Tyler, P., & Hall, J. W. (2018). Infrastructure as a complex adaptive system. Complexity, 2018.
157. Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. Reliability engineering & System safety, 121, 43-60.
158. Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. Structural safety, 36, 23-31.
159. Oxford Dictionaries, 2018. Available at https://en.oxforddictionaries.com.

160. Pan, L., Liu, P., Ma, L., & Li, Z. (2012). A supply chain based assessment of water issues in the coal industry in China. *Energy Policy*, *48*, 93-102.

161. Pant, R., Blainey, S., Hall, J., & Preston, J. (2015). Assessing risks to inform resilience: a criticality assessment of the British railway network. UCL STEaPP.

162. Pant, R., Hall, J. W., & Blainey, S. P. (2016). Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. European Journal of Transport and Infrastructure Research, 16(1).

163. Pant, R., Thacker, S., Hall, J. W., Alderson, D., & Barr, S. (2018). Critical infrastructure impact assessment due to flood exposure. Journal of Flood Risk Management, 11(1), 22-33.

164. PCCIP. (1997). CRITICAL FOUNDATIONS PROTECTING AMERICA'S INFRASTRUCTURES. The Report of the President's Commission on Critical Infrastructure Protection.

165. Pederson, P., Dudenhoeffer, D., Hartley, S., & Permann, M. (2006). Critical infrastructure interdependency modeling: a survey of US and international research. Idaho National Laboratory, 25, 27.

166. PENG, H. J., ZHOU, M. H., LIU, M. Z., ZHANG, Y., & HUANG, Y. B. (2009). A dynamic optimization model of an integrated coal supply chain system and its application. *Mining Science and Technology (China)*, *19*(6), 842-846.

167. Petit, F., Verner, D., Brannegan, D., Buehring, W., Dickinson, D., Guziel, K., Haffenden, R., Phillips, J., & Peerenboom, J. (2015). Analysis of critical infrastructure dependencies and interdependencies (No. ANL/GSS-15/4). Argonne National Lab.(ANL), Argonne, IL (United States).

168. Porteus, E. L. (1990). Stochastic inventory theory. Handbooks in operations research and management science, 2, 605-652.

169. RAIL MAP online. (2019). Historic railways, railroads and tramways. Available at: http://www.railmaponline.com/UKIEMap.php

170. Railway Codes. (2019). Engineer's Line References (ELRs). Available at: http://www.railwaycodes.org.uk/elrs/elr0.shtm
171. Rajeev, P., Kodikara, J., Robert, D., Zeman, P., & Rajani, B. (2014). Factors contributing to large diameter water pipe failure. Water asset management international, 10(3), 9-14.
172. Rao, K. V. (2015). Introduction to Transportation Infrastructure Systems Planning and Design. Available at: https://slideplayer.com/slide/6094148/
173. Reis, V. (2014). Analysis of mode choice variables in short-distance intermodal freight transport using an agent-based model. Transportation research part A: Policy and practice, 61, 100-120.
174. Rentizelas, A. A., Tolis, A. J., & Tatsiopoulos, I. P. (2009). Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renewable and Sustainable Energy Reviews, 13(4), 887-894.
175. RFG. (2020). Rail Freight Group. Who uses rail freight? Available at: http://www.rfg.org.uk/rail-freight/who-uses-rail-freight/
176. Rinaldi, S. M. (2004). Modeling and simulating critical infrastructures and their interdependencies. In System sciences, 2004. Proceedings of the 37th annual Hawaii international conference on (pp. 8-pp). IEEE.
177. Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Systems, 21(6), 11-25.
178. Rindsfüser, G., & Klügl, F. (2007). Agent-based pedestrian simulation: a case study of the Bern railway station. disP-The Planning Review, 43(170), 9-18.
179. Robert, B. (2004). A method for the study of cascading effects within lifeline networks. International journal of critical infrastructures, 1(1), 86-99.
180. Robson, C., Barr, S., Pregnolato, M., & Ji, Q. (2018). A spatiotemporal database framework for infrastructure systems analytics and modelling.
181. Roni, M. S., Chowdhury, S., Mamun, S., Marufuzzaman, M., Lein, W., & Johnson, S. (2017). Biomass co-firing technology with policies, challenges, and opportunities: A global review. *Renewable and Sustainable Energy Reviews*, *78*, 1089-1101.

182. Roorda, M. J., Cavalcante, R., McCabe, S., & Kwan, H. (2010). A conceptual framework for agent-based modelling of logistics services. Transportation Research Part E: Logistics and Transportation Review, 46(1), 18-31.
183. Rosenberg, G., & Carhart, N. (2014). Review of Potential Infrastructure Interdependencies in Support of Proposed Route HS2 Phase 2 Consultation.
184. Royal Academy of Engineering, 2011, Infrastructure, Engineering and Climate Change Adaptation -ensuring services in an uncertain future.
185. Royal Academy of Engineering. Infrastructures, Engineering and Climate Change Adaptation- Ensuring services in an uncertain future. (2011).
186. RSSB. (1998). Track Standards Manual -Section 8: Track Geometry. Railway Group Standard GC/RT5017 Issue Two Date December 1998.
187. RSSB. (2012). GE/RT8000/M3 Rule Book. Issue 1. Managing incidents, floods and snow.
188. RSSB. (2015). Review of the rules for the operation of trains through flood water.
189. RSSB. (2016). TRaCCA WP2 final report. Available from: http://www.rssb.co.uk/research-development-and-innovation/research-and-development/research-project-catalogue
190. RSSB. (2019). INITIAL REPORT TO THE MINISTER FOR RAIL. RAIL INDUSTRY DECARBONISATION TASKFORCE. January 2019.
191. Sandker, M., Campbell, B., Ruiz-Pérez, M., Sayer, J., Cowling, R., Kassa, H., & Knight, A. (2010). The role of participatory modeling in landscape approaches to reconcile conservation and development. Ecology and Society, 15(2).
192. Santella, N., Steinberg, L. J., & Parks, K. (2009). Decision making for extreme events: modeling critical infrastructure interdependencies to aid mitigation and response planning. Review of Policy Research, 26(4), 409-422.
193. Santos, J. R. (2006). Inoperability input-output modeling of disruptions to interdependent economic systems. *Systems Engineering*, *9*(1), 20-34.

194. Santos, J. R., & Haimes, Y. Y. (2004). Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. Risk Analysis: An International Journal, 24(6), 1437-1451.

195. Santos, J. R., & Haimes, Y. Y. (2004). Modeling the demand reduction input-output (I-O) inoperability due to terrorism of interconnected infrastructures. Risk Analysis: An International Journal, 24(6), 1437-1451.

196. Satumtira, G., & 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.

197. Schaschke, C. (2005). Fluid mechanics, worked examples for engineers. Published by institution of chemical engineers.

198. Schmid, F. (2018). Railway system engineering and integration. Materials for a MsC course by Birmingham Centre for railway research and education.

199. Schmidt, M. (2008). The Sankey diagram in energy and material flow management: Part I: History. Journal of industrial ecology, 12(1), 82-94.

200. Setola, R., & Theocharidou, M. (2016). Modelling dependencies between critical infrastructures. In Managing the complexity of critical infrastructures (pp. 19-41). Springer, Cham.

201. Setola, R., De Porcellinis, S., & Sforna, M. (2009). Critical infrastructure dependency assessment using the input–output inoperability model. International Journal of Critical Infrastructure Protection, 2(4), 170-178.

202. Seyoum, S. D., Vojinovic, Z., Price, R. K., & Weesakul, S. (2011). Coupled 1D and noninertia 2D flood inundation model for simulation of urban flooding. *Journal of hydraulic engineering*, *138*(1), 23-34.

203. Shuang, Q., Zhang, M., & Yuan, Y. (2014). Node vulnerability of water distribution networks under cascading failures. Reliability Engineering & System Safety, 124, 132-141.

204. Simpson, M., Ives, M. C., Hall, J. W., Kilsby, C. J., (2016). Chapter 6 Water supply systems assessment. The future of national infrastructure: A system-of-systems approach. Cambridge University Press.

205. Singh, A. N., Gupta, M. P., & Ojha, A. (2014). Identifying critical infrastructure sectors and their dependencies: An Indian scenario. International Journal of Critical Infrastructure Protection, 7(2), 71-85.

206. Sokhansanj, S., Kumar, A., & Turhollow, A. F. (2006). Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass and Bioenergy, 30(10), 838-847.

207. Srirangarajan, S., Allen, M., Preis, A., Iqbal, M., Lim, H. B., & Whittle, A. J. (2013). Wavelet-based burst event detection and localization in water distribution systems. *Journal of Signal Processing Systems*, *72*(1), 1-16.

208. Srirangarajan, S., Iqbal, M., Lim, H. B., Allen, M., Preis, A., & Whittle, A. J. (2010). Water main burst event detection and localization. In *Water Distribution Systems Analysis 2010* (pp. 1324-1335).

209. Stationary office, 2011, Climate Resilient Infrastructure: Preparing for a Changing Climate

210. Stationery office. (2011). Climate Resilient Infrastructure: Preparing for a Changing Climate. Presented to Parliament by the Secretary of State for Environment, Food and Rural Affairs by Command of Her Majesty May 2011.

211. Stergiopoulos, G., Kotzanikolaou, P., Theocharidou, M., Lykou, G., & Gritzalis, D. (2016). Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures. International Journal of Critical Infrastructure Protection, 12, 46-60.

212. Stoker, J. J. (1992). Water waves: The mathematical theory with applications (Vol. 36). Copyright 1958 by John Wiley & Sons. Wiley Classics Library Edition Reprinted, 1992.

213. Svendsen, N. K., & Wolthusen, S. D. (2007). Connectivity models of interdependency in mixed-type critical infrastructure networks. Information Security Technical Report, 12(1), 44-55.

214. Svendsen, N. K., & Wolthusen, S. D. (2007). Connectivity models of interdependency in mixed-type critical infrastructure networks. Information Security Technical Report, 12(1), 44-55.

215. Tabachnick, B. G., Fidell, L. S., & Ullman, J. B. (2007). Using multivariate statistics (Vol. 5). Boston, MA: Pearson.

216. TfL. London Underground Comprehensive Review of Flood Risk (LUCRFR). (2017). Transport for London

217. Thacker, S., Barr, S., Pant, R., Hall, J. W., & Alderson, D. (2017). Geographic hotspots of critical national infrastructure. Risk Analysis, 37(12), 2490-2505.

218. Thames Water. (2011). "Investing in our network: Replacing London's Victorian water mains." ⟨http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/2689.htm⟩.

219. Thames Water. (2016). Drinking Water Treatment. Available at: https://www.thameswater.co.uk/help-and-advice/water-quality/how-we-look-after-your-water/drinking-water-treatment

220. Thameslink Railway. (2018). Our route maps, downloadable route map for the Thameslink network. Available at: https://www.thameslinkrailway.com/destinations-and-offers/where-we-travel-to/our-routes

221. Thameslink Railway. (2019). Travel information. Available at: https://www.thameslinkrailway.com/travel-information

222. TISN. (2018). Trusted Information Sharing Network for critical infrastructure resilience. Australian Government. Available at https://www.tisn.gov.au/Pages/Critical_infrastructure.aspx

223. Tizghadam, A., & Leon-Garcia, A. (2008, November). On robust traffic engineering in transport networks. In IEEE GLOBECOM 2008-2008 IEEE Global Telecommunications Conference (pp. 1-6). IEEE.

224. Topographic maps. (2017). Available from: available at: http://en-gb.topographic-map.com/places/London-92172/

225. Tran, M., Hall, J., Nicholls, R., Hickford, A. J., Chaudry, M., & Watson, G. (2018). Sustainable Infrastructure. Sustainable Futures in the Built Environment to 2050: A Foresight Approach to Construction and Development, 117.

226. Trucco, P., Cagno, E., & De Ambroggi, M. (2012). Dynamic functional modelling of vulnerability and interoperability of Critical Infrastructures. Reliability Engineering & System Safety, 105, 51-63.

227. TWUL. (2017). Thames Water trunk mains strategic review. Final report. Date of issue: 2 October 2017.

228. UK Trade Info. (2015). Available at: https://www.uktradeinfo.com/Statistics/RTS/Pages/default.aspx

229. United Nations Security Council. (2018). The protection of critical infrastructure against terrorist attacks: Compendium of good practices. Office of counter-terrorism.

230. Uppsala University. (2002). Numerical Analysis II. Information Technology Department of Scientific Computing.

231. Utne, I. B., Hokstad, P., & Vatn, J. (2011). A method for risk modeling of interdependencies in critical infrastructures. *Reliability Engineering & System Safety*, *96*(6), 671-678.

232. Van Eeten, M., Nieuwenhuijs, A., Luiijf, E., Klaver, M., & Cruz, E. (2011). The state and the threat of cascading failure across critical infrastructures: the implications of empirical evidence from media incident reports. *Public Administration*, *89*(2), 381-400.

233. VELCO. (2018). Vermont Electric Power Company. What is transmission. Available at: https://www.velco.com/about/learning-center/what-is-transmission

234. Voinov, A. (2017). Participatory modelling for sustainability. Encyclopaedia of Sustainable Technologies, 2017, Pages 33-39

235. Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. Environmental Modelling & Software, 25(11), 1268-1281.

236. Voinov, A., Jenni, K., Gray, S., Kolagani, N., Glynn, P. D., Bommel, P., Prell, C., Zellner, M., Paolisso, M., Jordan, R., Sterling, E., Olabisi, L. S., Giabbanelli, P. J., Sun, Z., Page, C. L., Elsawah, S., BenDor, T. K., Hubacek, K., Laursen, B. K., Jetter, A., Basco-Carrera, L., Singer, A., &, Young, L. Jessica Brunacinic, Alex Smajglx& Sterling, E. (2018). Tools and methods in participatory modeling: Selecting the right tool for the job. Environmental Modelling & Software, 109, 232-255.

237. Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce S.A., & Ramu, P. (2016). Modelling with stakeholders–next generation. Environmental Modelling & Software, 77, 196-220.

238. Wallace, W. A., Mendonça, D., Lee, E., Mitchell, J., & 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.

239. Wang, S., Hong, L., & Chen, X. (2012). Vulnerability analysis of interdependent infrastructure systems: A methodological framework. *Physica A: Statistical Mechanics and its applications*, *391*(11), 3323-3335.

240. Wang, S., Hong, L., Ouyang, M., Zhang, J., & Chen, X. (2013). Vulnerability analysis of interdependent infrastructure systems under edge attack strategies. *Safety science*, *51*(1), 328-337.

241. Winkler, J., Dueñas-Osorio, L., Stein, R., & Subramanian, D. (2011). Interface network models for complex urban infrastructure systems. Journal of Infrastructure Systems, 17(4), 138-150.

242. Woodburn, A. (2017). The impacts on freight train operational performance of new rail infrastructure to segregate passenger and freight traffic. *Journal of Transport Geography*, 58, pp.176-185.

243. World Health Organisation and UNICEF (2014). Progress on drinking water and sanitation – 2014 update. Geneva, Switzerland, World Health Organisation/UNICEF.

244. Wrachien D. DE. and Mambretti S. (2009). Dam-Break Problems, Solutions and Case Studies. WIT Press Transactions on State-of-the-art in Science and Engineering.

245. Wu, T., J. Blackhurst, and V. Chidambaram. 2006. “A Model for Inbound Supply Risk Analysis.” Computers in Industry 57: 350–365.
246. Yearley, S., Cinderby, S., Forrester, J., Bailey, P., & Rosen, P. (2003). Participatory modelling and the local governance of the politics of UK air pollution: a three-city case study. Environmental Values, 12(2), 247-262.

247. Zetica. (2007). Summary report on drainage survey for Kentish town and Carlton road junction. ZR004-06-R1-A. 14th March 2007.

248. Zimmerman, R. (2001). Social implications of infrastructure network interactions. Journal of Urban Technology, 8(3), 97-119.
249. Zio, E., & Sansavini, G. (2011). Modeling interdependent network systems for identifying cascade-safe operating margins. IEEE Transactions on Reliability, 60(1), 94-101.

Appendix A Identification of climate change risk

Climate UK (2012) summarises the climate change risks to Yorkshire and Humber. The key risks and potential implications identified in the report are summarised in Table 37. The report suggests that flooding (including coastal flooding) is a major risk to the region.

Table 37 Summary of Climate-change risks to Yorkshire and Humber identified by Climate UK (2012)

1. Type or risks	2. Implications
3. Flooding 4. (including coastal erosion)	5. Multiple flood impacts on business such as to premises, stock, logistics and travel by staff or customers. 6. Disruption to transport infrastructure impacting on the community, customers and logistics. 7. Disruption to IT infrastructure, communications and energy from flooding – with knock on effects on other sectors. 8. Exacerbation of existing health conditions, such as asthma and respiratory illnesses and increased risk of mental health issues resulting from multiple impacts of severe flooding.
9. Increased temperature	10. Changing nature of health needs
11. Storm/wind damage	12. Multiple impacts on business premises, housing and built assets
13. Continuing snow and ice	14. Multiple impacts on business premises, housing and built assets

Figure 134 shows the Strategic Flood Risk assessment around the area. Figure 135 Flood risk map around Immingham Port shows the flood risk map around Immingham Port with known extents of previous flooding events. These figures, and data from the Risk of Flooding from Rivers and Sea dataset (Environment Agency, 2015), indicate that there is only limited scope for “moderate” risk of flooding for the focussed section between Barnetby and Brocklesby (specifically located around small streams to the south west of Brocklesby Junction). However, there is a notable coastal-flooding risk around Immingham port. And the routes to the west of Barnetby Junction are also affected by flooding associated with the rivers Ouse and Trent. Figure 134 and Figure 135 are extracted from Strategic Flood Risk Assessment 2010 (SFRA) conducted by North East Lincolnshire Council. Flood Zone 2 indicates having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% – 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% – 0.1%) in any year. Flood Zone 3 means land is assessed as having a 1 in 100 or greater annual probability of river flooding (>1%), or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year.

Further analysis by British Geological Survey (BGS) concurred that the Barnetby-Brocklesby section is subject to only a low- medium risk from a single (culverted) stream, but that the sections to the west of Barnetby and to the east of Brocklesby are subject to higher ratings of flood risk, relating to rivers and coastal inundation (RSSB, 2015).

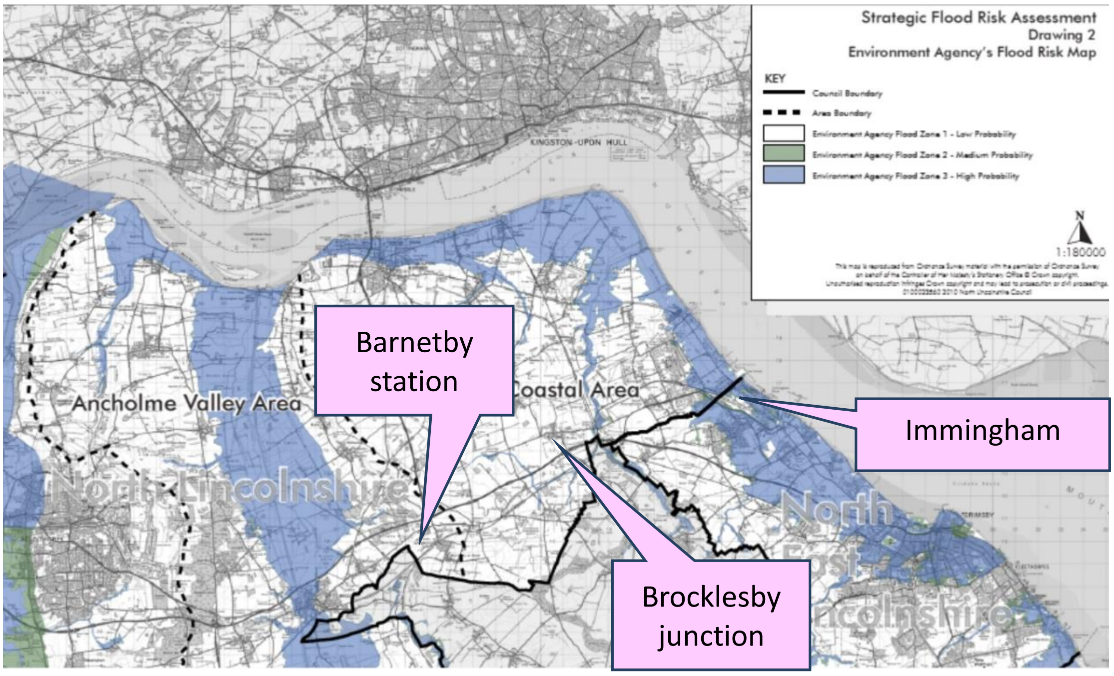


Figure 134 Flood risk map around the case study area

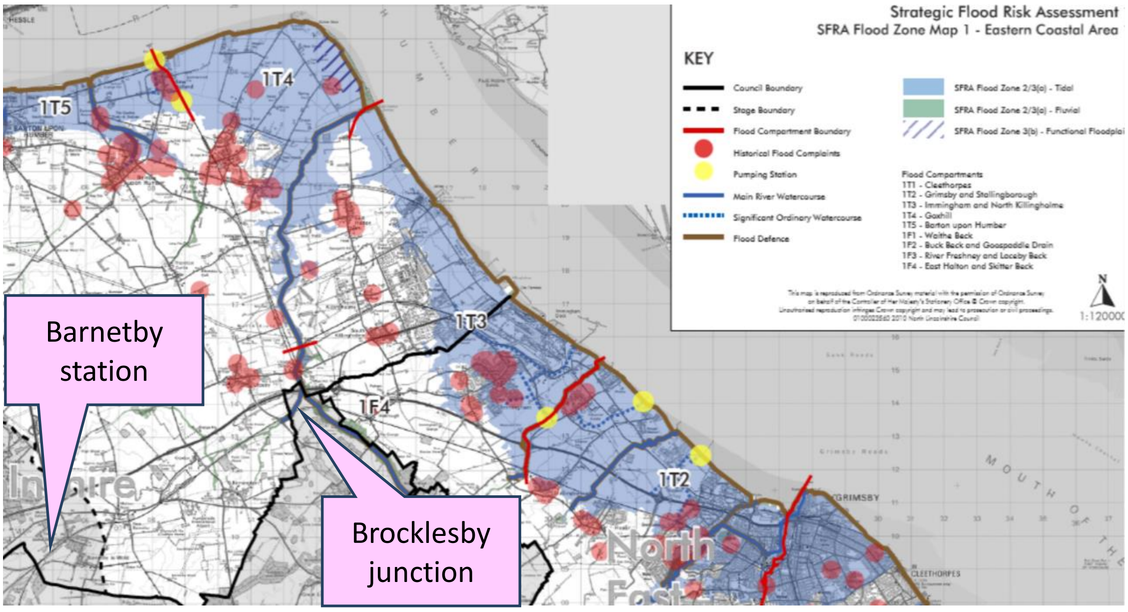


Figure 135 Flood risk map around Immingham Port

Indeed, a sea-level rise and storm surge in December 2013 caused flooding in Immingham Port, which was forced to close for one week. In terms of relative susceptibilities, stakeholders noted that the east coast is more prone to storm surges than the west coast.

Climate UK (2012) also suggests increased temperature, storm/wind damage, and continuing snow and ice as climate change risks for the region. However, the route stakeholder has chosen flooding as their primary concern in the first instance, and the following case studies will focus on it.

Appendix B Background Data Analysis of the Drax-Immingham Port Case Study Area (an Example of Landslide Susceptibility Data from British Geological Survey)

Overview of Landslide Susceptibility

BGS has previously developed a high-level landslide susceptibility model for Network Rail. The details can be found in BGS report CR/15/031 and are summarised here:

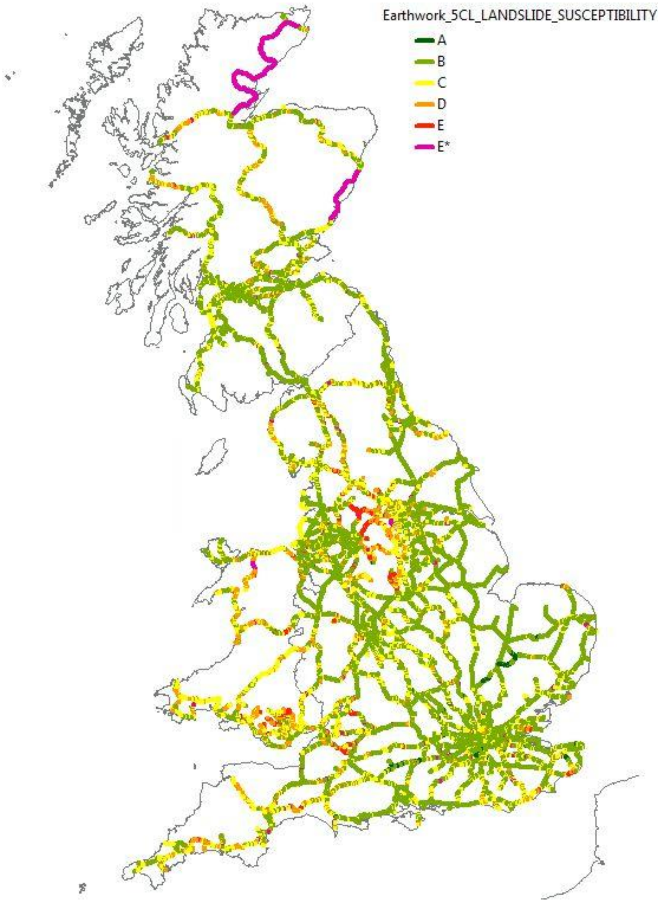


Figure 136. High-level landslide susceptibility

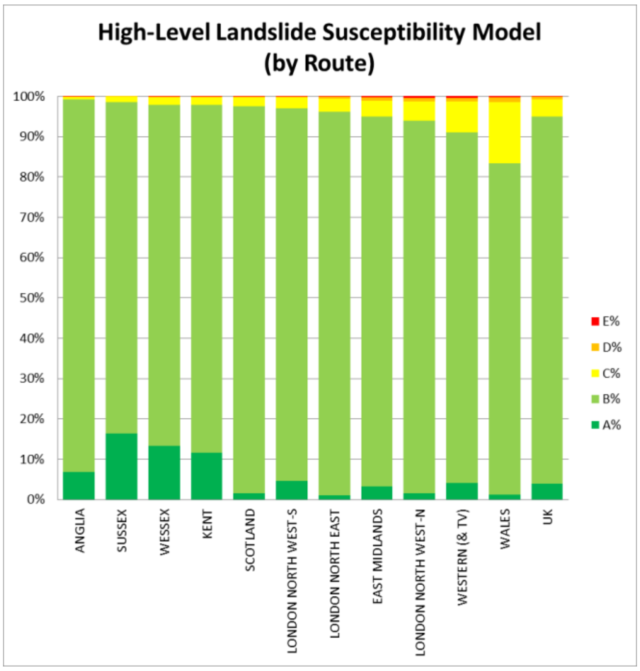


Figure 137. High-level landslide susceptibility by route

Figure 136 and Figure 137 are derived from the licensable BGS GeoSure dataset (http://www.bgs.ac.uk/products/geosure/). This 1:50,000 scale national dataset is suitable for screening assets at strategic, operational and local scales. It provides an overview of relative threats of six common geohazards: (Landslides, Swell-shrink clays, Compressible ground, Collapsible ground, Dissolution and Running sand flood). Each hazard being rated A (best case) to E (worst case) and provided with a narrative description of issues that may be found in each class. The above analysis is of the susceptibility of natural slope failure (Landslides). Each 5-chain length has been interpolated against the Geosure dataset to find the worst-case susceptibility rating (the interpolation including a ‘proximity search, as well as spatial intercept analysis). The ratings are described here http://www.bgs.ac.uk/products/geosure/landslidesPHI.html and vary from A (*No indicators for slope instability identified*), to E (*Very significant potential for slope instability. Active or inactive landslides may be present*). No specific action level is identified as the ratings are deployed across a range of users. For the examples shown above, a strategic level of study would possibly consider all chainages rated C,D or E to be ‘of interest’). This NR study includes an additional class E* which is a modification aimed at providing a strategic overview of chainages where observed failures or noted CIV028 reports had occurred. Summary statistics of the rating are possible (e.g. at route level as shown above, for comparison with WRACCA analyses).

Note that this dataset provides a susceptibility rating and is not a risk assessment.

Overview of Drax – Immingham Port Landslide susceptibility

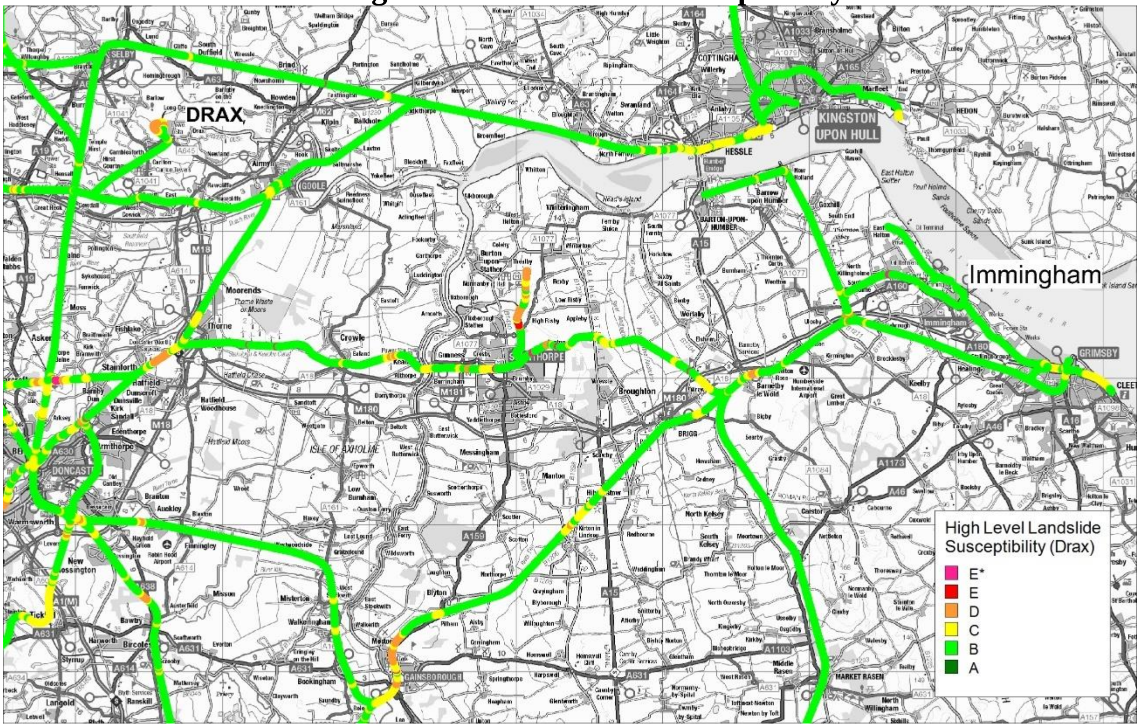


Figure 138. High-level landslide susceptibility around Drax and Immingham Port

Figure 138 depicts the GeoSure: Landslide dataset compared with the 5-Chain length (5-CL) data for the Drax-Immingham route. The 5-CL assets are highlighted according to susceptibility rating (Worst case category E and E* are red, best case category A, is green). Most of the chain-lengths are within the A and B categories, but note that there are several zones of E and D rating along the main routes from the port to power stations, on the ‘DOW’ and ‘MAC3’ ELR sectors. Summary statistics (such as those shown in Figure 139) for chainages ‘at risk’ can be calculated for the various ELR sectors (and the likely diversionary routes).

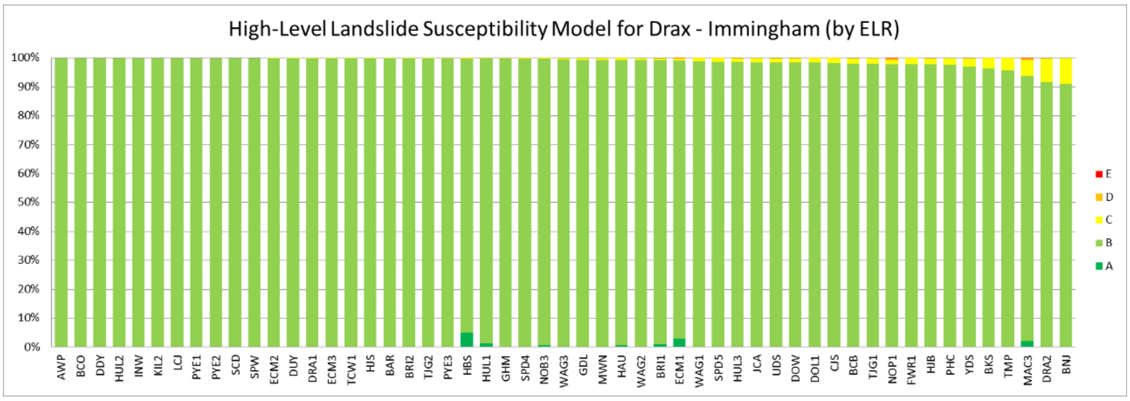


Figure 139. High-level landslide susceptibility around Drax and Immingham Port by ELR sector

Overview of Barnetby Station - Brocklesby Junction Landslide susceptibility

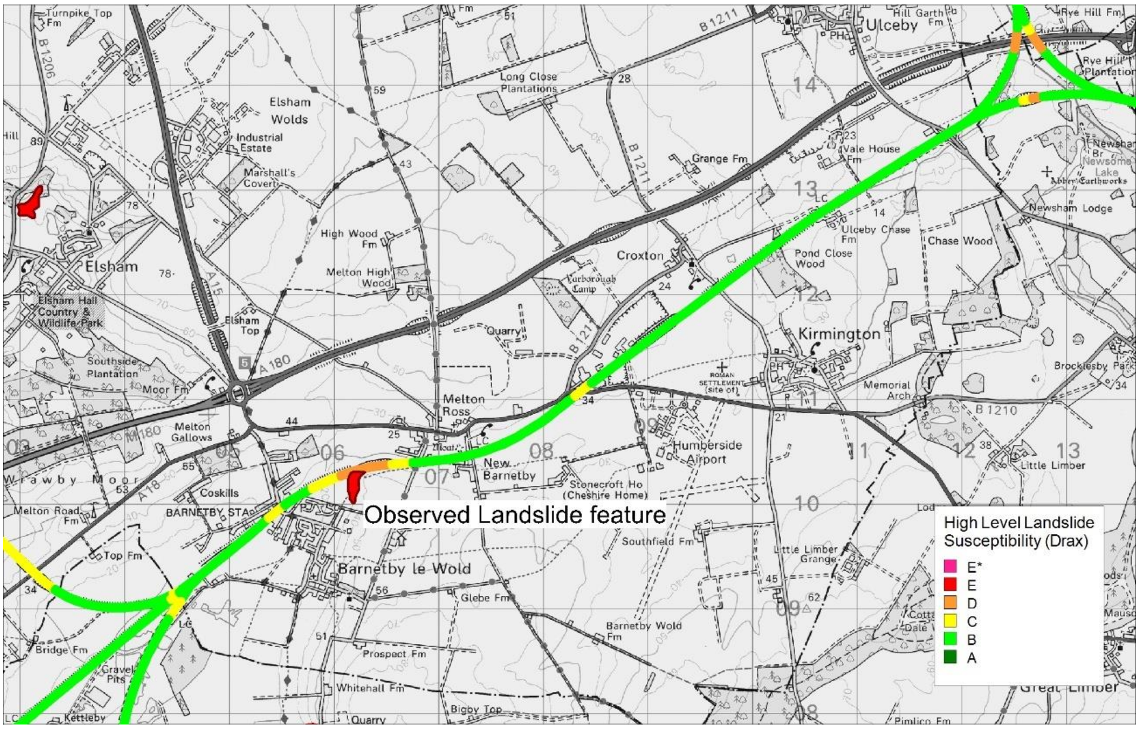


Figure 140. Landslide susceptibility

In Figure 140, the GeoSure: Landslide dataset is compared with the 5-Chain length (5-CL) data for the case study sector of Barnetby – Brocklesby (ELR = MAC3). Most of the sector is given a B rating for landslide susceptibility. However, north of Barnetby and in the vicinity of the Brocklesby Junction, there are higher ratings of C (*Possibility of slope instability problems after major changes in ground conditions)* and D (*Significant potential for slope instability with relatively small changes in ground conditions*). The D rating is associated with a known and mapped landslide feature (identified on geological maps (shown as a red polygon). Both categories clearly indicate that 'changes' to local conditions (be that adjacent groundwork activities, water balance/flows in the environment or other forms of ground loading, could induce some failure mode.

For this relatively short sector but high criticality sector, a further analysis of slope stability is warranted. That could include a walk-over survey, or a higher resolution model, using NR LiDAR) and bespoke modelling of water management and material strength. The sector passes through the chalk escarpment, an analysis of rockfall (from engineered slopes in cuttings), and possibly Karstic features could also be considered.

Overview of Barnetby Station - Brocklesby Junction Geohazards: Running Sand

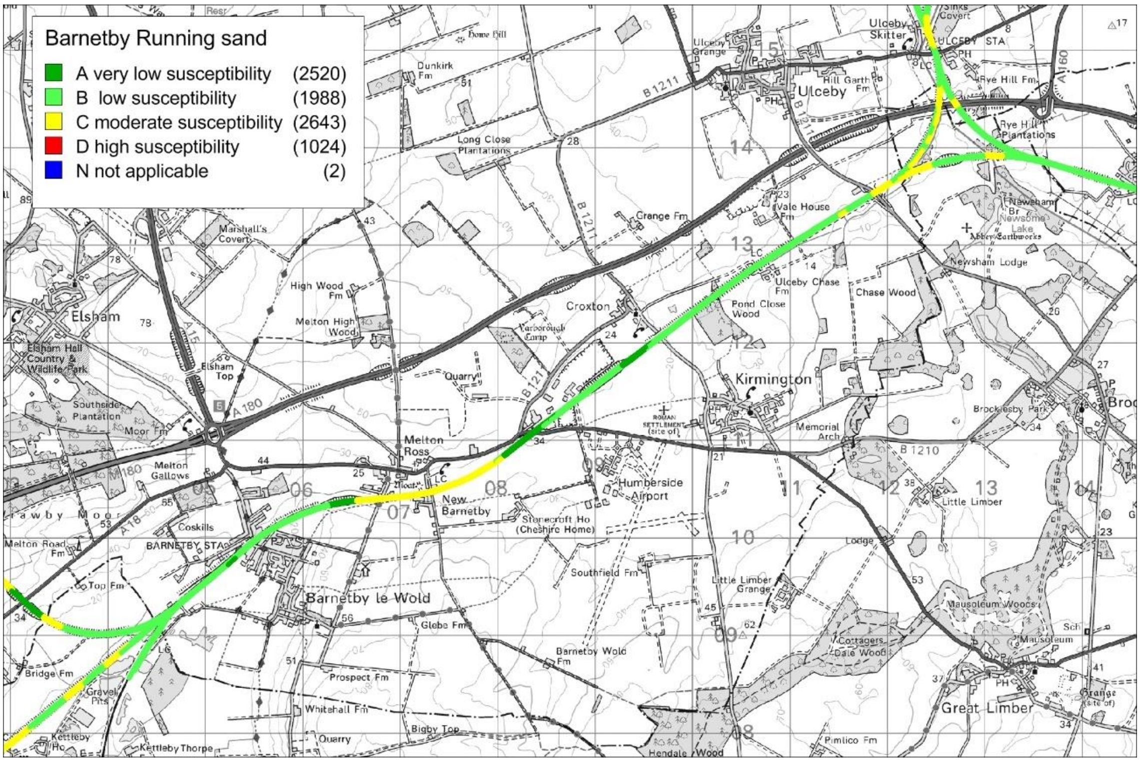


Figure 141. Running sand susceptibility

The Case study workshop highlighted a specific scenario whereby bridge foundations failed where a co-located water main had burst and exfiltration of water had flushed away foundation-support. Figure 141 shows the distribution of susceptibility to ‘running sands’. Running sands are deposits that can become mobilised (fluidised) by moving ground water, or anthropogenic activities such as excavation or exfiltration. As a result, they can be flushed from around and beneath foundations (similar to scour). In the above image, most of the route is classed as Low susceptibility, with some chainage of moderate susceptibility and thus a potential to be ‘sensitive’ to running. A local to national screening of 5-Chain Lengths, compared with their proximity to known mains water supplies, may offer a traffic-light warning system for Route asset managers, so that they can liaise with their water-industry counterparts and share knowledge about where co-located services may prove to be a mutual threat.

Appendix C Implication of a rail infrastructure Failure (Outcomes of the Workshop)

Scenario A

Below are the main points of the workshop:

Expected duration

- If a control room is damaged, it means that all signal utilities are damaged. If the signalling is washed out, then the internal power system is also washed out completely (cables for power are washed out).
- The worst-case scenario would be if the surge tides repeat 3 times. Repeated surge tides normally occur once in 4-5 hours (re-irritating damage).
- Even if we manage to place the signal box at a higher level there are still some signal-related assets on the ground which might be affected.
- If a terminal is damaged, it takes approximately 3 months to recover. The biggest challenge here is to bring all professionals together to build it again.
- If the surge occurs in January or February, the consequences of the flooding is greater than if it happens in December. This is because normally November is drier and therefore the river/ ground water level is lower.

Impact

- Access of rail and other staff to the site will be restricted due to the flooding.
- Because of flooding and interrupted services, trains will be suspended at stabling locations around the network. This can cause in further disruptions in services. Normally these stabling locations are at plants where they can stop. This will not allow the trains travelling from other routes to get into the plants. Also, these trapped trains all over the network interrupt the traffic for recovery procedures.
- Another effect might be related to the staff working hour. For example, if the driver starts working after a few hours of delay he/she might have already exceed the working hour.
- There are two junctions in the area of the scenario for discussions. The one on the flood plain is crucial for oil transport. If this junction is out of service for long-term then an issue for delivering oil to airports (such as Birmingham airport) will raise.
- The loss of coal/biomass supply to power stations can be covered but not all.
- If one power station is flooded this would not impact the power operation as National Grid will defend. Long-term breakage might be an issue.

- In addition to coal/biomass traffic, the importance of trains from Lindsay oil refinery to inland oil depots, which are supplying fuel to airports, as well as trains to the steel work at Scunthorpe should not be underestimated.

Figure 142 shows the flipchart produced in the workshop in scenario A.

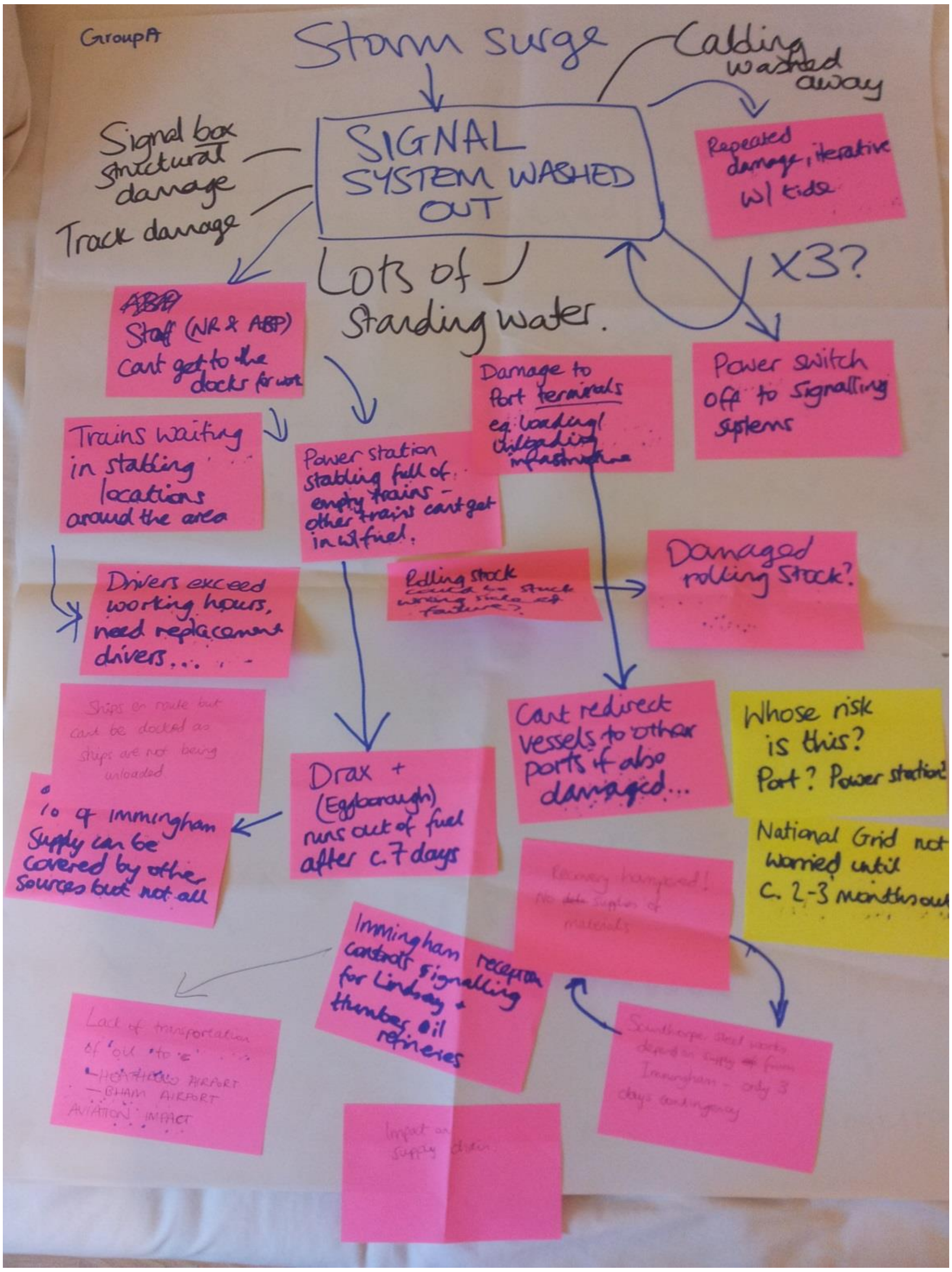


Figure 142. Flipchart produced for discussion around Scenario A.

Scenario B

Below are the main points of the workshop:

Expected duration

- A minimum closure of six weeks would be expected for a temporary measure (to pass trains at a reduced capacity) to be established. Permanent repair would require six months.

Impact

- Access of rail and other staff to the site will be restricted due to the flooding.
- If road is used to alternatively transport coal and biomass, it would cause congestion on local, trunk and motorway networks.
- Such congestion would impact local communities and cause environmental damage.
- If a severe congestion happens because of Lorries due to a disruption at or on the route to Immingham Port, there will be an arrangement similar to Operation Stack on M20 (M25 to Dover).
- Diversion of ships to west-coast ports would impact Transpennine route and motorway networks.
- Disruption in coal/biomass supply would lead to power cuts
- Local passenger service can be replaced with bus service

Figure 143 shows the flipchart produced in the workshop in scenario B.

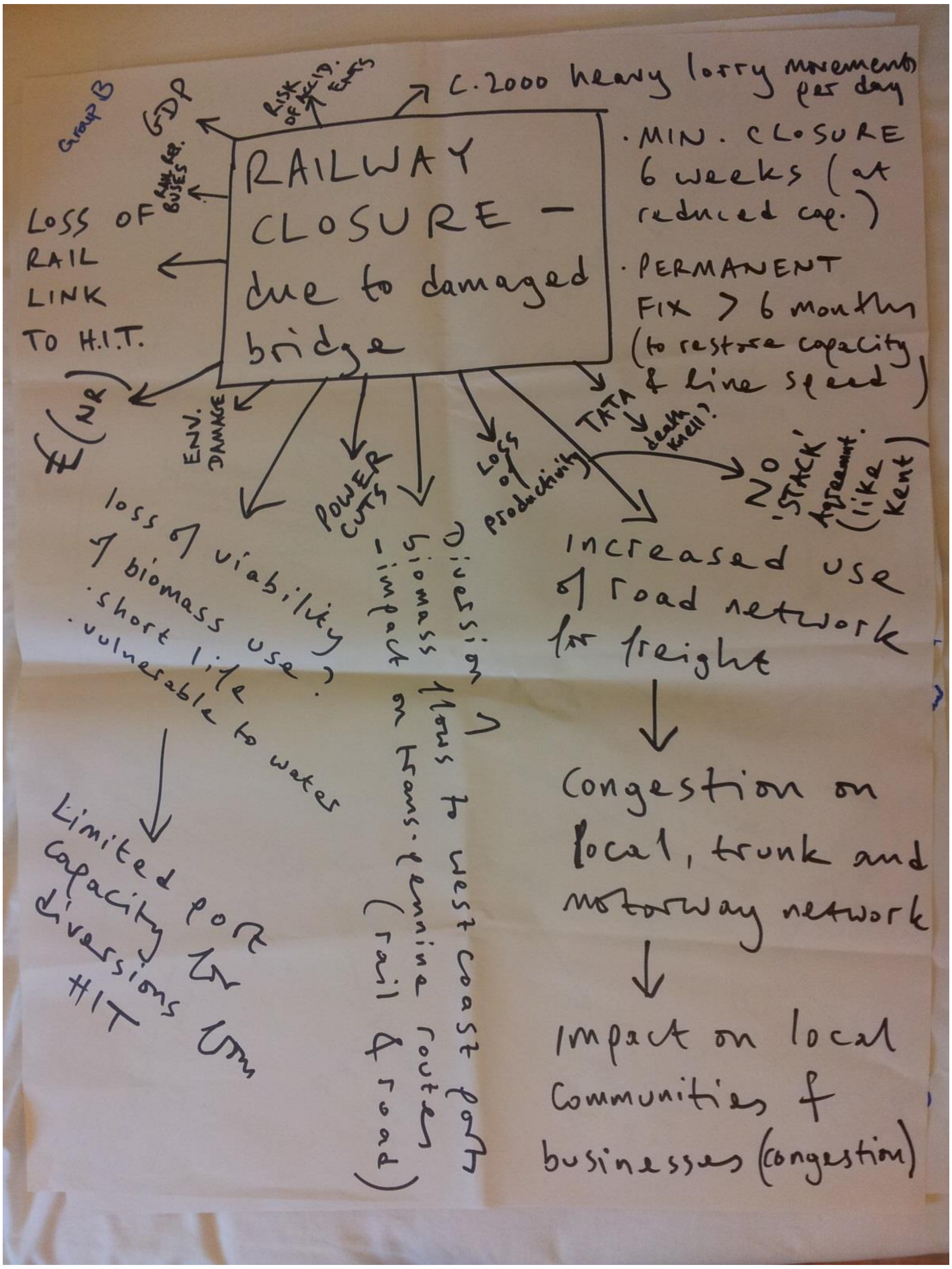


Figure 143. Flipchart produced for discussion around Scenario B

Scenario C

Below are the main points of the workshop.

Expected duration

- Two weeks for temporary recovery.
- An interview with a Network rail Project Engineer after the workshop suggests that a temporary recovery would need 3-4 weeks with full repair 4 months.
- It would be easier to close the road until the bridge is repaired. It is possible to use parliamentary powers to get railway up and running first.
- If a water main has a problem like this, we would ask questions: how happen, what's the catchment, utilities type. Then there will be a discussion to find out the details of the assets and the legal teams of Yorkshire water and Network Rail will talk to each other.

Impact

- Local passenger service can be replaced with bus service
- If the road is closed, it is necessary to take account of road closers and impact to public.
- Rail have impacts of freight and passenger
- Network rail doesn't own drainage underneath. Would bring attention to outside party if evidence of a problem. Do examine track supporting structures, but not drainage.
- Each infrastructure owner does not consider how its asset (or failure of it) would affect the other types of infrastructure and waits until there is a failure. This may be because of funding issues: who will pay the costs of inspections for the sake of somebody else?
- This type of incidents is not limited to water. There are high pressure gas mains and oil pipelines across the railway. All have different policies.

On the planning side, every infrastructure owner needs to understand the connectivity of the networks of other types of infrastructure. It would be ideal to share the data. Note that as no infrastructure owner has a perfect dataset (because assets are old there is always something missing/wrong), there can be mechanism that if data (of the assets of another infrastructure owner is found to be wrong, this can be reported to the owner).

Figure 144 shows the flipchart produced in the workshop for scenario C.

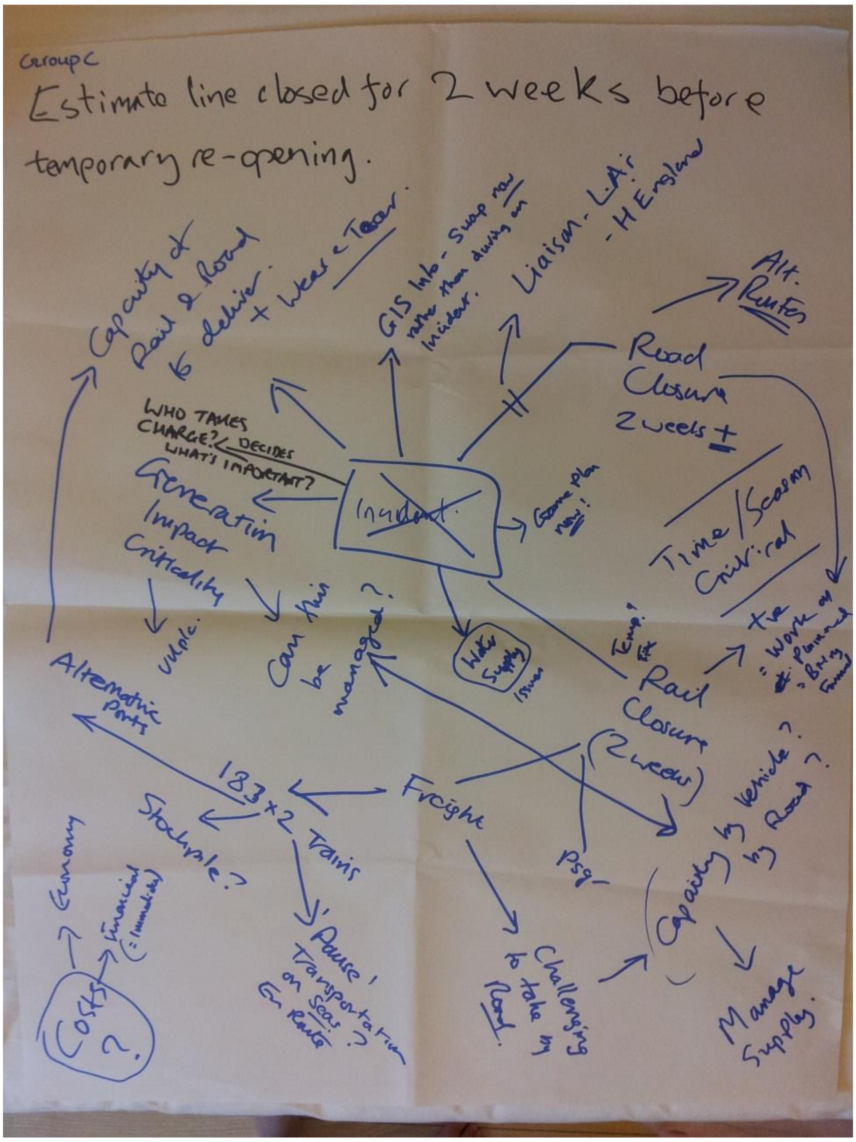


Figure 144. Flipchart produced for Scenario C

Appendix D Potential solutions proposed by stakeholders

One session of the stakeholder workshop was allocated to generate potential solutions (options) for the scenarios created (see Section 4.5.1.2). In total, 25 solutions were developed. Whereas, some solutions are primarily railway specific, others need a national approach (involving non-rail sectors) for execution and funding.

To provide recommendation for further research, the following eleven solutions were selected from the 25 solutions proposed at the workshop. Solutions 1 to 6 concern the railway infrastructure whereas Solutions 7 to 11 require collaboration with other sectors (including the energy and road sectors).

Table 38 Solutions for further analysis

No	Scenario	Solutions
1	**A, B**	Standardisation of infrastructure to make replacement & maintenance easier
2	**A, B, C**	Remote monitoring of infrastructure
3	**B, C**	Building a new alternative route to increase diversion capacity
4	**B**	Rapidly deployable temporary bridging
5	**A**	Move signal box to Rail Operating Centre in York[1] or a place safer from flooding
6	**B**	Build a gantry in front of the rail bridge to prevent lorries from striking the bridge
7	**B**	Adapt "Operation Stack" in roads when a railway-originated disruption causes heavy congestion on local roads by lorries
8	**A, B, C**	Better sharing of contingency plans & options between stakeholders Develop a decision-making mechanism for emergency situations

[1] This recommendation was made based on the assumption that the signal box in the port has much equipment, and if the box were flooded and the equipment were severely damaged it would take a long time for their repair.

		Use of Resilience Direct[2]
9	**A, B, C**	Development of alternative biomass infrastructure at ports, transport systems and power stations including additional storage and alternative transport networks (e.g. canals)
10	**A, B, C**	Develop data share mechanism between different types of infrastructure users (rail, water, road) (to help the recovery of assets at intersections)
11	**A, B, C**	Encourage local users and staff to report symptoms (road users, water engineers, controllers)

As can be seen in the table, whereas some solutions are primarily engineering ones (e.g. Solution 4, Bailey Bridge), management and liaison solutions were also proposed (e.g. Solution 8, Cross-sectoral contingency plan). A separate piece of work is required to further investigate the feasibility of each solution.

[2] Resilience Direct is a web-based network in which practitioners concerning critical infrastructure can work together in risk communication. Further information can be found at https://www.gov.uk/guidance/resilient-communications

Appendix E Matlab Code

Note that, the appendix is added to provide additional information to the examiners, but will be removed from the version to be submitted as the final version and thus to remain in the public domain.