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A Systems-based Approach to the Identification of Enterprise/Infrastructure Interdependencies as a Precursor to Identifying Opportunities to Improve Infrastructure project Value/Cost Ratios

Abstract

The bulk of the investment needed for renewal of infrastructure in the United Kingdom will have to come from the private sector; however, private investors are reluctant to provide funding unless projects have attractive value/cost ratios and effective value capture mechanisms are in place. The Government has recognised that infrastructure interdependencies can help increase value and reduce cost; but, it remains difficult for investors to be sure they will make an adequate return. New business models are required to overcome these problems. They must take account not only of infrastructure-centred interdependencies (interdependencies between infrastructures themselves) but also enterprise-centred interdependencies (interdependencies between social and economic enterprises and the infrastructures they use). The often complex and closely coupled nature of enterprise and infrastructure systems can stand in the way of identifying these interdependencies; however, model-based systems engineering techniques offer a framework for dealing with this complexity. This paper describes research that the iBUILD project is doing to support local infrastructure delivery, through the development of a methodology for modelling the interdependencies between infrastructure and the enterprises that use it; this is as a precursor to identifying opportunities to improve infrastructure project value/cost ratios. The methodology involves: identifying the suite of policy, strategy and operational documents relating to the enterprise-of-interest; eliciting system data from the documents and integrating it using CORE 9, a powerful system modelling tool produced by Vitech Corporation, to create an enterprise system model; and, generating N^2 diagrams from the model to identify the interdependencies.

Introduction

UK infrastructure currently faces a number of challenges: much of it is old (in some cases over 150 years old) and in need of renewal; increasing demands are being placed on it as population grows; infrastructures themselves are increasingly interdependent, risking propagation of local failures through the wider network; and, the bulk of the investment needed for renewal will have to come from private investors. Urgent action is required to tackle these problems and ensure the United Kingdom (U.K.) has the infrastructure it needs for the future [CST, 2009], [ICE, 2010].

Infrastructure interdependencies bring risks, but they also bring opportunities: the Government has recognised their potential to encourage private investment by improving the value/cost ratios of infrastructure projects. In terms of cost reduction, infrastructure interdependence-based opportunities include co-location of services (for example, cables and pipes sharing the same trench), and more efficient (and therefore cheaper) scheduling of street works; while, opportunities to improve value include dual-use of infrastructure, such as a road embankment acting as a flood defence barrier, or an electricity cable being used to carry data [H.M.Treasury, 2011a].

In spite of these opportunities, it remains difficult for investors to be sure they will make an adequate return on their investment, or capture all of the value that their investment helped to generate. It is often unclear whether there will be sufficient user demand at the tariff level required for an economic return; in such cases it may be necessary for government to step in with some form of guarantee in order to get investors on-board [FT.com, 2013]. And even when the economic case can be made, there is often the risk that investors will not be able to capture value generated beyond the immediate boundaries of the project: for example, investors in a new road may be able to capture value through receipt of user tolls, but other value associated with the road, such as reduced traffic congestion and a resultant increase in property prices, could be lost.

New business models are required to help overcome these problems. The iBUILD research consortium, with funding from the Engineering and Physical Sciences Research Council (EPSRC), and the Economic and Social research Council (ESRC), is studying the development of new infrastructure business models to support local infrastructure delivery [H.M. Treasury, 2011a]. It is pursuing three research themes: the business of interdependence; re-thinking infrastructure value; and, issues of scale in local delivery. These are brought together in a number of integrative case studies, and findings will be used as the basis for further research, co-created in conjunction with commercial and public project-partners.

The new business models must take account not only of infrastructure-centred interdependencies (interdependencies between infrastructures themselves), but also enterprise-centred interdependencies (interdependencies between users engaged in an enterprise and the infrastructure that supports it). Business and social activities, facilitated by infrastructure, generate value for civilised society. The ability to identify value from the perspective of those involved in an enterprise, and capture it, will help to improve infrastructure project value/cost ratios and attract private investment capital; however, before this can happen, it is necessary to identify for a given enterprise, what enterprise/infrastructure interdependencies there are.

The often complex and closely coupled nature of user and infrastructure systems can stand in the way of identifying these interdependencies; systems engineering techniques offer a framework for overcoming the problem. Current methods for modelling infrastructure interdependencies rely on information elicited from domain experts, which brings with it risks of information subjectivity and model variability [Ehlen et al, 2013]. A more repeatable and objective methodology is required to increase confidence in the validity of the models produced.

This paper describes the work that iBUILD is doing to develop a methodology for modelling the interdependencies between enterprises and infrastructure, as a precursor to identifying opportunities to improve infrastructure project value/cost ratios. The methodology is based on model-based systems engineering (MBSE) techniques and involves: identifying the suite of policy, strategy and operational documents relating to the activity-of-interest; eliciting system data from the documents and integrating it using CORE 9, a powerful system modelling tool produced by Vitech Corporation, to create an activity system model; and, generating N^2 diagrams from the model to identify the interdependencies.

The paper begins with a brief overview of interdependency. The difference between infrastructure-centred and enterprise-centred approaches is illustrated using as an example the project 'Broadband for the Rural North'. The paper then introduces model-based systems engineering, and describes the objective and repeatable methodology used to create the enterprise-centred models. An example of a hypothetical port is used to show how the model can help to identify its interdependencies with the supporting infrastructure. The paper finishes with conclusions and an overview of future planned work.

Infrastructure Interdependence

Infrastructure interdependence is the term commonly used to refer to both dependencies and interdependencies between infrastructures. Dependence is defined as, ‘a connection established between two infrastructure assets, where the condition of one asset is influenced by the other, but not vice versa’; whereas, interdependence is, ‘the reciprocal dependence between two assets that establishes bi-directional connectivity between network elements’ [Pant et al, 2012]. An example of interdependence is shown in the diagram of Figure 1. If the power generator has to operate at reduced capacity and, as a result, can no longer provide electricity to the water pumping station, the pumping station will no longer be able to provide water to the power generator. Ultimately, both the power generator and the water pumping station may cease to operate.

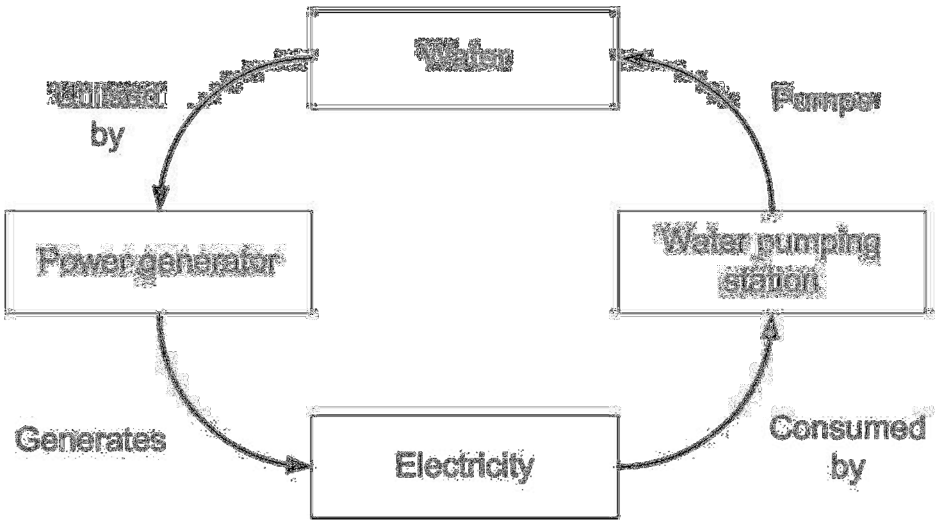

Figure 1: A Diagram Showing an Example of Infrastructure Interdependence

Interdependence has been an important aspect of infrastructure studies since the 1990s. While the poor condition of the United States’ infrastructure emerged as an issue in the 1980s [NCPWI, 1988], it was national security concerns in the 1990s that led to the establishment of the President’s Commission on Critical Infrastructure Protection, and a shift in focus to infrastructure interdependence. The PCCIP’s 1997 report [PCCIP, 1997] described the dangers of uncontrolled interdependencies, but did not provide a framework for thinking about or analysing them. The paper by Rinaldi et al [Rinaldi et al, 2001] rectified this situation, providing a conceptual framework for addressing infrastructure interdependencies that could serve as the basis for further research.

The framework proposed by Rinaldi et al characterises infrastructure interdependence using the six dimensions shown in the diagram of Figure 2. The Environment dimension refers to the fact that infrastructures influence, and are influenced by, wider environmental considerations, such as developments in the fields of technology or health and safety. Coupling and response behaviour concerns how, and the degree to which, infrastructures are linked together, and how that affects their response to unexpected change. Infrastructure characteristics refer to those factors that help to define the scope of interdependency analysis: for example, following a disruptive event, the time period over which the impact is analysed will have an important bearing on the results. Types of failure concerns the way in which a disruptive event in one part of the system, may affect the wider network; and, the state of operation refers to the influence position in a system's operational cycle may have.

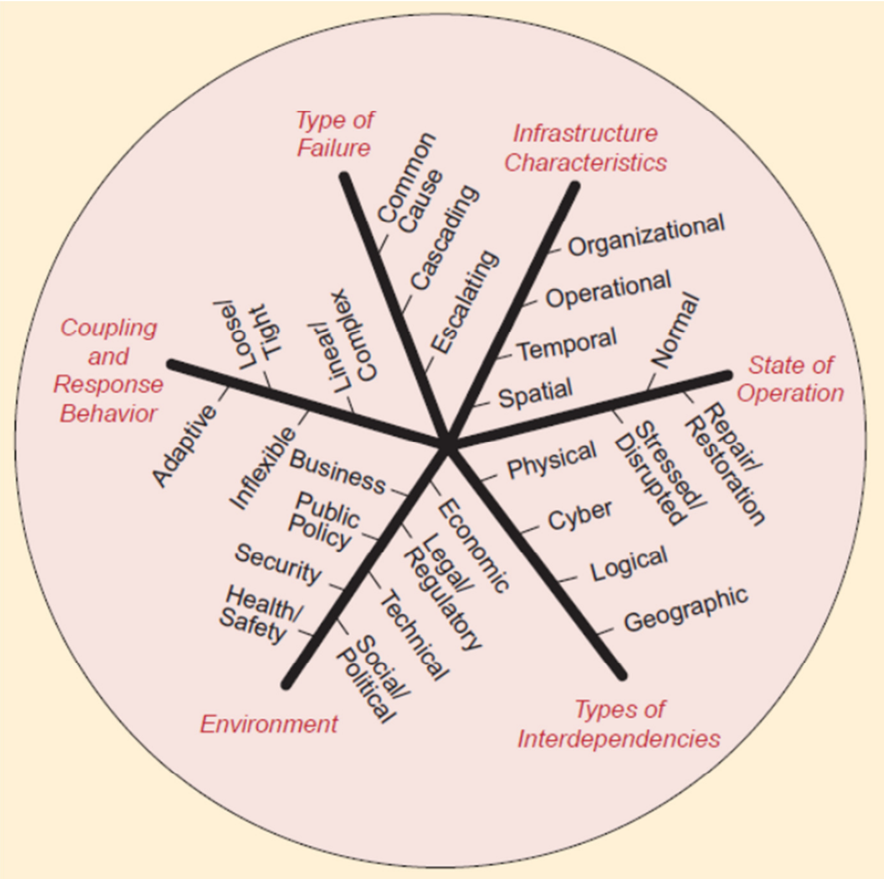

Figure 2: A Diagram Showing the Six Dimensions Characterising Infrastructure Interdependence [Rinaldi et al, 2001]

The sixth dimension is type of interdependence. Physical interdependence arises from a physical linkage between the inputs and outputs of two or more infrastructures. It fits closely the definition by Pant et al, and the arrangement illustrated by the diagram in Figure 1. Cyber interdependence refers to web-generated interdependencies. Many infrastructures now depend on information supplied over the web for their reliable operation; consequently, they are dependent on the proper working of communications networks. Geographic interdependence arises from the location of infrastructures relative to one another. Rinaldi et al deem two infrastructures to be geographically interdependent simply by virtue of co-location, even though there may be no physical links between them: for example, a pipe and a cable buried in the same trench would be classed as geographically interdependent. Finally, logical interdependence is something of a 'catch-all': it covers any two or more infrastructures, where the state of one is linked to the others via a mechanism that is not a physical, cyber, or geographic connection.

The U.K. Government has recognised the potential for some interdependencies to support private investment by improving the value/cost ratios of infrastructure projects. In terms of cost reduction, opportunities arising from geographical interdependence include co-location of services (for example, cables and pipes sharing the same trench), and more efficient (and therefore cheaper) scheduling of street works; while, opportunities to improve value include dual-use of infrastructure, such as a road embankment acting as a flood defence barrier, and from a physical interdependence point-of-view, an electricity cable being used to carry data.

Work on infrastructure network interdependence is on-going: for example, at the National Infrastructure Analysis and Simulation Center in the United States [NISAC], and at the Infrastructure Transitions Research Consortium in the United Kingdom [ITRC]. Mapping of interdependencies has shown how complex the situation can be (see Figure 3). Research is underway to understand: how failures in one system propagate into others; what the impact of failure might be on the wider economy; and, how infrastructure networks might be made more resilient.

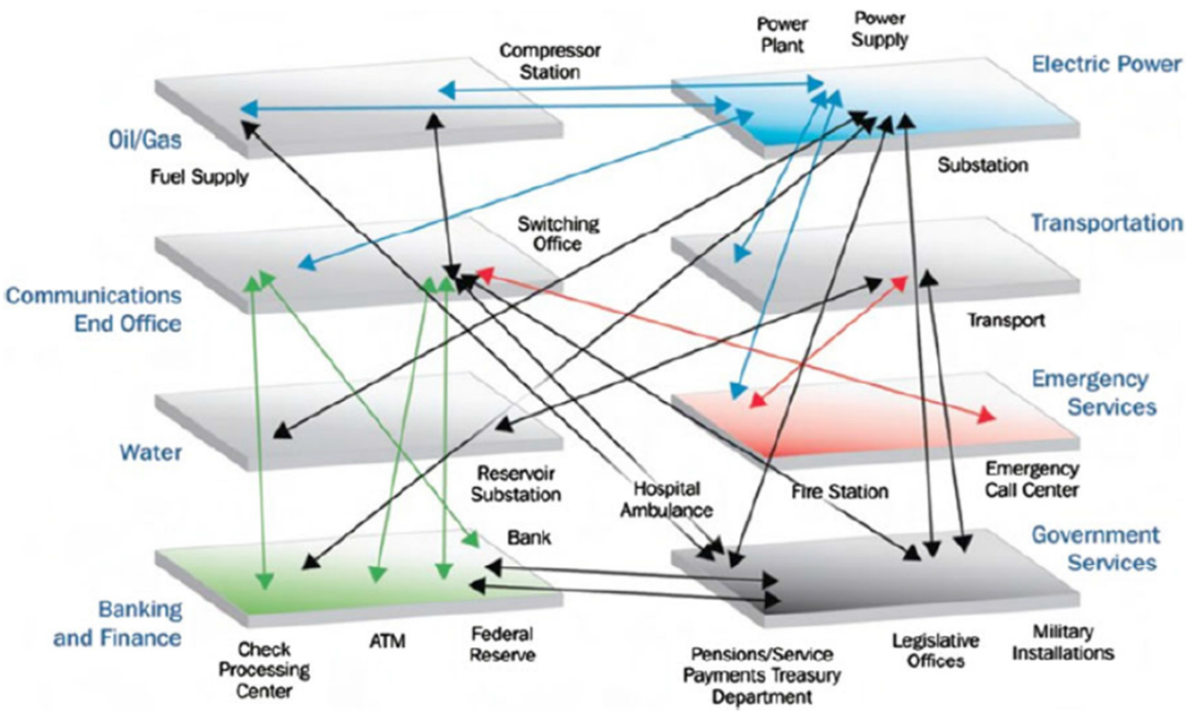

Figure 3: A Diagram Showing Typical Infrastructure Interdependencies [Ehlen et al, 2013]

Research carried out so far therefore, has been, almost exclusively, from an 'infrastructure-centred' viewpoint. It has helped identify the opportunities to improve infrastructure project value/cost ratios described above, but is limited in what it can do, because it fails to acknowledge that infrastructure is not an end in itself, but there to facilitate the activities that generate value for civilised society. The 'real' value of infrastructure arises from the various business and social enterprises that use it.

A new viewpoint therefore, is required: one that identifies the interdependencies between infrastructure and the value-generating enterprises undertaken by infrastructure users; in short, an 'enterprise-centred' viewpoint. From this viewpoint it will be easier to see how any given infrastructure contributes to enterprise value generation; and, easier to allocate, and even capture, that value for the relevant infrastructure, thus resulting in improvements to the value/cost ratio.

The 'Enterprise-centred Approach: 'Broadband for the Rural North'

The Broadband for the Rural North (B4RN) project is an example of an enterprise-centred approach to infrastructure provision. It demonstrates how monetary, and non-monetary, value arising from enterprise/infrastructure interdependencies, can be captured and used, in conjunction with cost reduction, to achieve the value/cost ratio necessary to support development and implementation of novel, and successful, business models.

The UK Government has a policy of rolling out, across the country, so-called 'Next Generation Broadband' (NGB): that is, broadband with download speeds of 30Mbps, or better. There is, however, a problem: the only way to provide this service to the 10% of the population who live in deeply rural areas is to lay fibre optic cables all the way to each of the properties concerned (known as Fibre to the Home - FTTH); and, this is prohibitively expensive. What might therefore, be viewed as 'normal' business models, do not work in this case: the fees that commercial broadband providers must charge for FTTH to earn an economic return, are too high to be affordable to most, if not all, of the potential users.

This places rural-dwellers at a serious disadvantage to the rest of the population, because they cannot access a wide range of important online services, and therefore, cannot reap the benefits associated with them. Research has shown that access to the internet can create: benefits through higher educational attainment for children; access to employment opportunities for workless adults; improved standards of living for older people; and, increased democratic engagement and access to information. If just 3.5% of unemployed non-internet users found a job by getting online it would deliver a net economic benefit of £560m; and each contact and transaction with government switched online could generate savings of between £3.30 and £12 [Forde, 2013].

To overcome this problem, a community company (B4RN) has been established to undertake the supply, installation and operation of a full FTTH network, starting with eight rural parishes in the north-west of England. B4RN is not a traditional 'for profit' company, though there is the chance of future returns for its shareholders; instead, it is a co-operative in which a group of individuals have coupled novel cost reduction methods with the potential to capture enterprise/infrastructure, interdependence-related value personal to each of them, to produce a business model that supports connection to the NGB network.

Cost reduction has been achieved in a number of ways: fibre is being laid across land owned by members of the co-operative, rather than in the public highway; much of the installation work is being carried out by members in lieu of paying a connection charge; and, those members buying shares are receiving tax relief through the Government's Enterprise Investment Scheme. Value capture comes from the potential benefits available to members through access to online services. It is difficult to make an objective assessment of monetary value for some of the services, such as access to a variety of news and entertainment services; but, that does not matter, because members (and people in general) are very good at making 'fuzzy' assessments of value, which they convert into a willingness to make a monetary payment for access.

B4RN is therefore, an example of the benefit that can come from adopting an enterprise-centred viewpoint. In this case, the enterprise consists of the individuals in the scheme going about their day-to-day activities, facilitated by high speed broadband (and other infrastructures), generating (often non-monetary)value in the process and equating that value with a willingness to pay for a reduced-cost internet connection. It could, however, take any number of forms: for example, an extension to an existing maritime port, where the owners create a business model based on opportunities arising from interdependencies between the port and its supporting infrastructure, such as railways, road, ICT and power supply.

Identifying Interdependencies: A Model-based Systems Engineering: Approach

The interfaces between enterprises and the infrastructures they use are often complex; this makes it difficult to identify enterprise/infrastructure interdependencies. Creating models of enterprise-centred systems can help overcome this problem; however, current methods of interdependence modelling rely on the input of domain experts, with the risk of subjective and variable output. iBUILD is exploring the feasibility of using a model-based systems engineering (MBSE) methodology, developed on an earlier EPSRC-funded project [Bouch et al, 2013] to create objective and repeatable models of existing enterprise/infrastructure systems.

MBSE is defined as the 'formalised application of modelling to support (system development)' (INCOSE, 2007); it joins modelling with systems engineering techniques, to create an integrated view of the system of interest (Long et al, 2011). Within MBSE, iBUILD is using a so-called 'middle-out' approach to create models of existing enterprise-centred systems; this requires: clear definition of the system boundary; elicitation of system data, ideally from an objective source, and; integration of that data to create the model.

The iBUILD modelling methodology defines the boundary of the system of interest in terms of the suite of related policy, strategy and operational/procedural documents, identified using the repeatable search method shown indicatively in the diagram of Figure 4. The process starts with high-level policy documents and works down through increasing levels of detail to enterprise operating processes and procedures. The high level document (referred to as 'key policy' document in Figure 4) makes reference to a number of documents, shown in the diagram as second level references; those documents in turn have references (third level references), and so on to produce an expanding, branching diagram. The diagram does not, however, branch indefinitely: some documents start to repeat (shown grey); or, do not have any references (shown blue); or, are deemed not relevant to the system of interest (shown red). The process continues until the circle at the end of every branch is grey, blue or red. The documents signified by the green circles then form the suite of documents for the system.

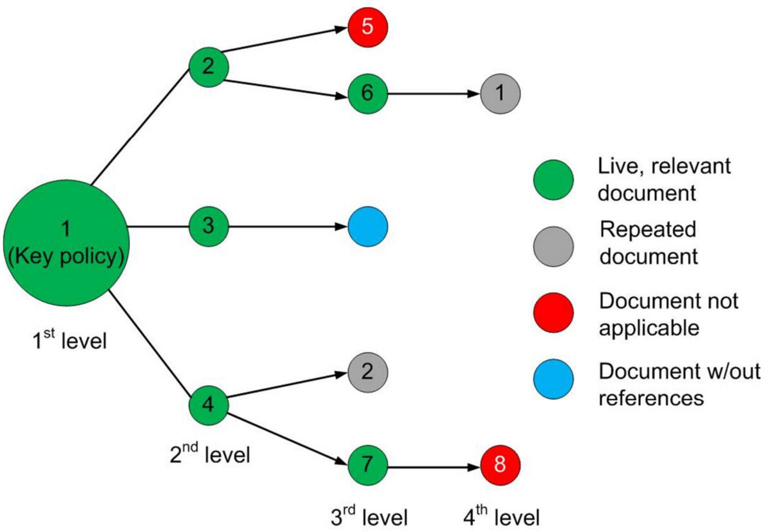

Figure 4: Indicative Diagram of the Document Search Method

System data elicitation involves reading through the documents identified by the search method and picking out the entities that taken together describe a system. The entities include: requirements, which describe what the system should do; functions, which describe what the system does; components, which are the physical parts of the system; and items, which include flows of information between functions and components.

Data integration and model creation is achieved using CORE 9, a powerful system modelling tool produced by Vitech Corporation in the United States [Vitech, 2012]. Essentially, CORE 9 is an entity/relationship/attribute database, where the system entities (functions, components, data items etc.), together with their attributes, are linked together by relationships. This approach captures the interfaces between the entities, and makes the model useful for identifying interdependencies. A high-level outline of the CORE 9 schema is shown in Figure 5.

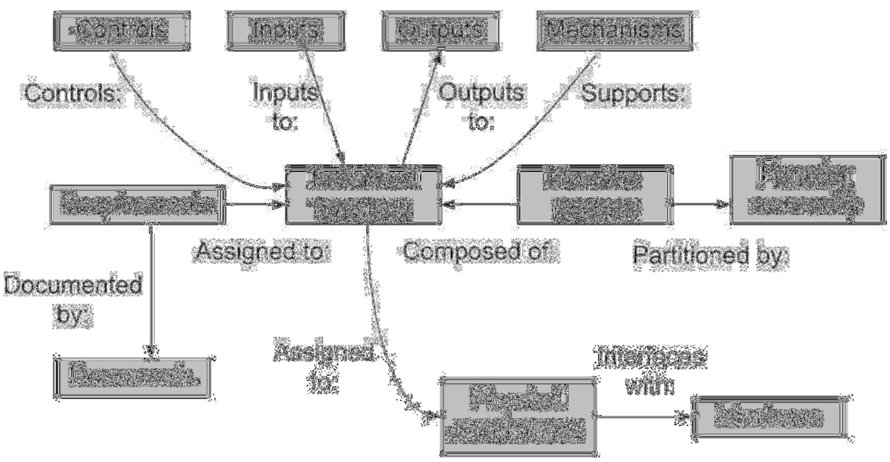

Figure 5: Indicative Diagram of an Entity-Attribute-Relationship Database Schema

Example of Enterprise/Infrastructure System Model: Hypothetical Port

The modelling methodology has been demonstrated using a hypothetical port as an example of an enterprise/infrastructure system. The work is not yet complete; however, the findings are sufficient to illustrate how the methodology works and the sort of results that might be expected.

To identify the documents defining the boundaries of the system, the Government's National Infrastructure Plan 2013 (NIP 2013) was chosen to kick-of the search process. The table in Figure 6 shows a summary of the results so far, with analysis of references at the third level almost complete. The references identified fall mainly into the governmental areas of policy, reports, legislation and regulation; this is probably to be expected bearing in mind that the search started with a policy document. The table shows only a limited number of infrastructure manager documents; this may reflect the decision to start with policy and the fact that the search process is still only in its early stages; but, may also be an early indication that these documents are regarded as commercially sensitive and therefore, not publically available. Access to these documents is crucial to model building; if the top-down search fails to identify them, a bottom-up approach will be required, involving negotiating with the infrastructure managers for access to the documents.

Document Type	**1st Level**	**2nd Level**	**3rd Level**
Legislation			11
Government policy	1	10	20
Government reports		5	21
National data		4	9
Regulation		2	11
Industry reports		1	2
Consultancy		1	6
Infrastructure manager		1	2
International		1	
Total	1	25	82

Figure 6: Table Showing the Results of the Document Search

The documents that have emerged from the search process so far have been analysed to identify the infrastructure sub-systems. The diagram in Figure 7 shows the high-level infrastructure system at the centre, surrounded by the infrastructure sub-systems covered in the documents. The arrows indicate relationships between the higher and lower levels: in this case they show that the high-level system is 'built from' the lower level sub-systems.

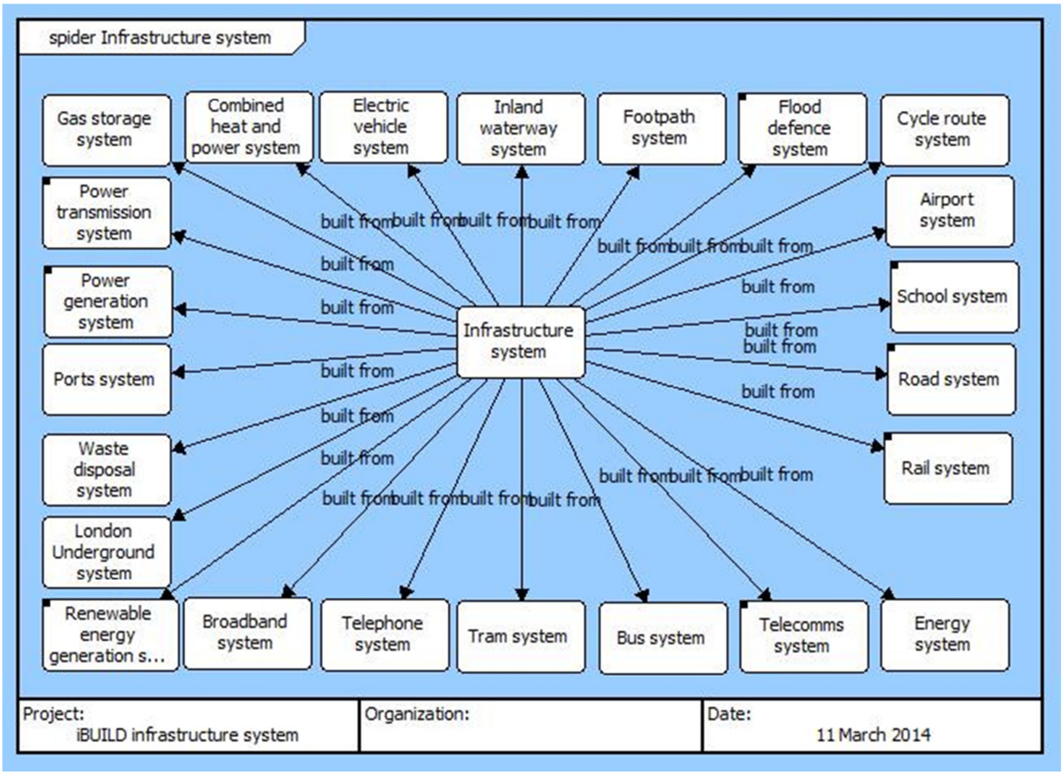

Figure 7: Diagram Showing the Infrastructure System and its Sub-systems

Work remains to be done to identify objectively the relationships between the port and the other infrastructure sub-systems; however, to illustrate the modelling process indicative relationships are shown in the diagram of Figure 8. The diagram is saying that operation of the port may involve interfacing with the infrastructure sub-systems shown by the arrows on the diagram: these are the interfaces at which enterprise system interdependencies may occur. The interdependencies, however, are high-level and of limited use in helping to identify opportunities for value/cost ratio improvement. Decomposition of the port system's functionality is required in order to show the interdependencies in more detail.

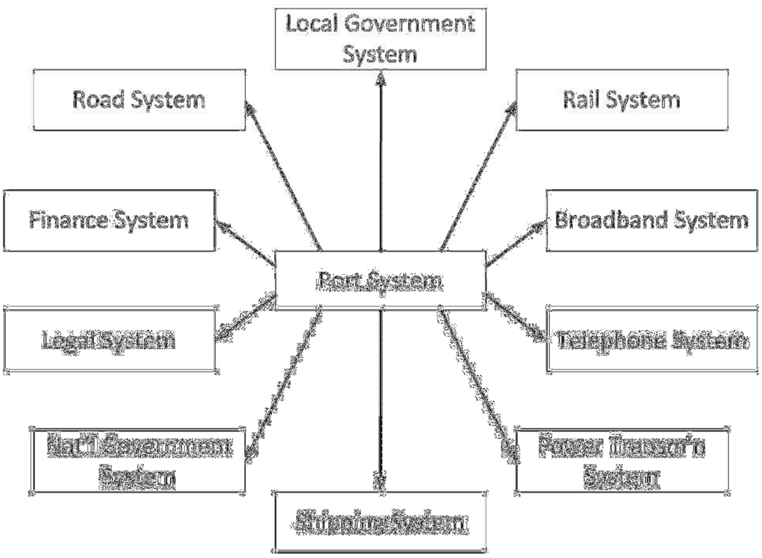

Figure 8: Diagram Showing Indicative Port Interdependencies

The diagram in Figure 9 shows an assumed set of high level functions describing the operation of the port; the functions are shown on the diagonal running from top left to bottom right. All other boxes on the diagram show events (event boxes) that trigger the functions: for example, in the top left, arrival of the train triggers the function ‘Port unload train’. The event boxes also indicate interdependencies between the port and its supporting infrastructure: for example, the train arrival event indicates that there is an interdependence between the port and the railway system. Similarly, the ‘birth booking’ and ‘birth confirmation’ events indicate interdependencies between the port and the ICT system.

Conclusions

This paper shows in outline that model based systems engineering can be used to identify interdependencies between enterprises and their supporting infrastructure. It suggests a repeatable method for identifying the suite of documents describing the system of interest; and, shows how objective data elicited from the documents can be integrated using CORE 9 to create a system model. The N^2 diagram derived from the model can help to identify the interdependencies.

Work is required to develop the model further and prove conclusively that the proposed model based systems engineering approach is effective.

Future Work

The methodology needs to be tested on a ‘real world’ problem; there are two possible candidates at the moment: planned development of the Port of Tyne; and, the arrival of HS2 in Birmingham. The latter is already one of iBUILD’s case studies, and is therefore, perhaps, the prime candidate.

The ‘Broadband for the Rural North’ example of the enterprise-centred approach, used in this paper, is relatively small scale. The methodology needs to be tested on something larger scale, perhaps involving an enterprise, or enterprises, that are more overtly commercial

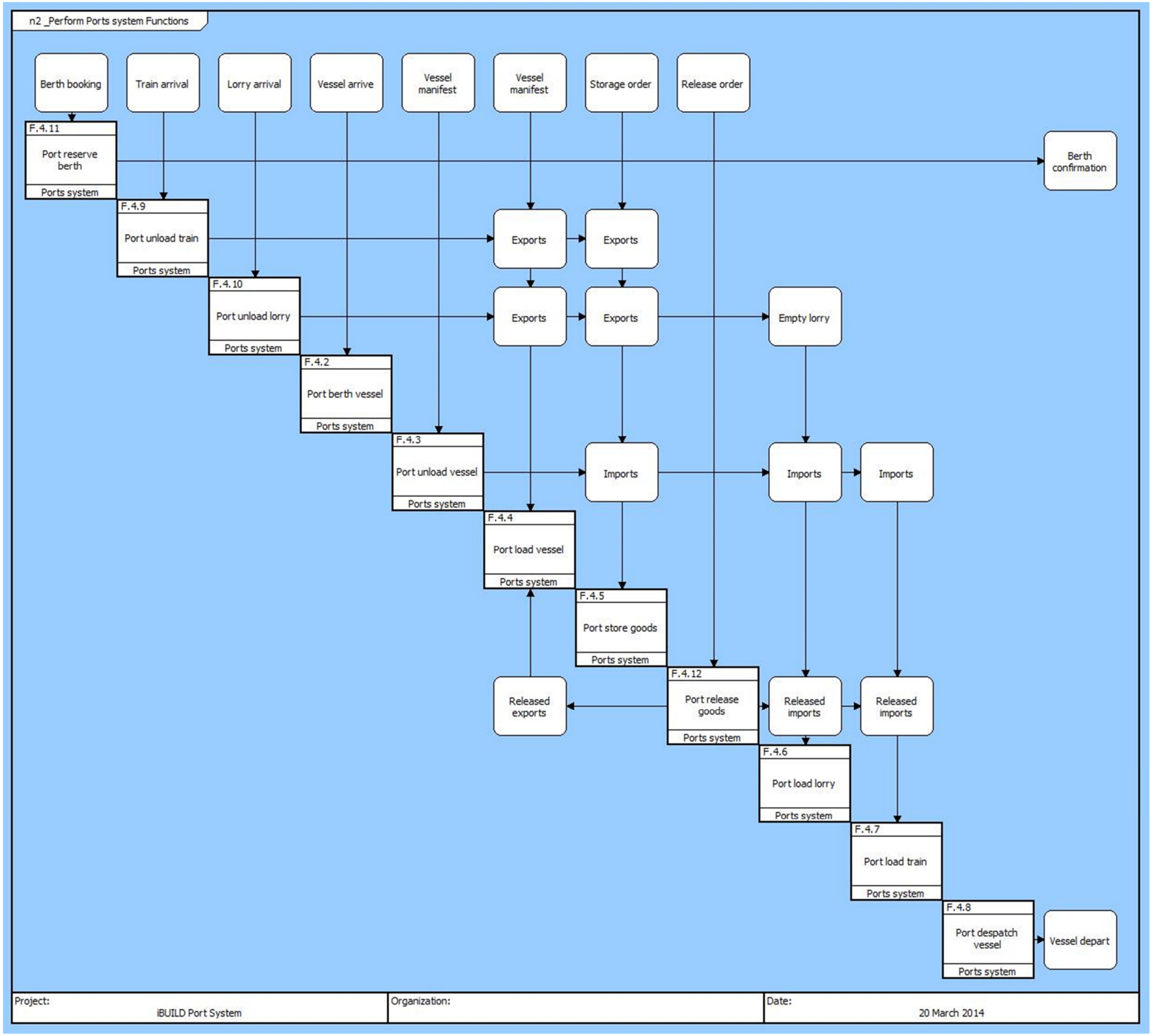

Figure 9: N^2 Diagram for a Hypothetical Port Showing the Principal Functions and Related Interdependencies

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