Modelling Infrastructure Interdependency at the City Scale: A Novel Methodology Applied to Birmingham's Solid Waste Management System

Bouch, Christopher; Rogers, Christopher; Baker, Christopher

Citation for published version (Harvard):
Bouch, C, Rogers, C & Baker, C 2015, Modelling Infrastructure Interdependency at the City Scale: A Novel Methodology Applied to Birmingham's Solid Waste Management System. in Proceedings of the ISNGI conference 2015.

Modelling Infrastructure Interdependency at the City Scale: A Novel Methodology Applied to Birmingham's Solid Waste Management System

Christopher J. Bouch (corresponding author), University of Birmingham, United Kingdom
Email: c.bouch@bham.ac.uk

Christopher J. Baker, University of Birmingham, United Kingdom
Email: c.j.baker@bham.ac.uk

Christopher D. F. Rogers, University of Birmingham, United Kingdom
Email: C.D.F.ROGERS@bham.ac.uk

Keywords
Infrastructure; system; modelling; business model

Abstract
The amount of solid waste produced by cities is growing. The European Union is tackling this problem with a move towards an integrated approach to solid waste management, aimed at creating economically, environmentally and socially sustainable solutions. The pace at which change can take place will be constrained by the high sunk costs and long life cycles of the existing infrastructure; and, system implementation will require significant investment from the private sector, which will only be forthcoming if project costs can be lowered and investors can be sure they will capture their fair share of the value generated. Models of existing solid waste management systems are helpful in providing a base from which to identify opportunities that leverage infrastructure interdependencies to create schemes with attractive value/cost ratios. This paper describes research into the feasibility of creating such models using a methodology previously developed for, and successfully applied to, the UK's railway infrastructure system.

Introduction
Global sustainability is being adversely affected by continuing growth in the volume of solid waste produced by cities. Cities generated approximately 1.3 billion tonnes of solid waste in 2012, and it is estimated this will increase to 2.2 billion tonnes per annum by 2025. Waste is becoming increasingly complex and hazardous to treat, and yet waste problems are often handled in a fragmented and uncoordinated manner, with the focus on end-of-pipe solutions rather than on prevention measures and integrated approaches [1]. There is, therefore, an urgent need to work towards policies and actions to improve solid waste management systems, notably by designing, implementing, and operating the supporting systems that deliver greater value in terms of sustainability and resilience.

In response to this challenge, waste management in the European Union is evolving to reduce negative environmental and health impacts, and contribute to an energy and resource-efficient economy [2]. The Waste Framework Directive promotes the concept of life-cycle thinking in waste policies [3]. The aim is to ensure development of future waste management systems that are environmentally, economically and socially sustainable. It is clear that no one single method of waste disposal can achieve this for all waste types; instead, waste management systems need to be built up from closely-related processes and integrated effectively [4].

Against this background, Birmingham City Council (BCC) is reviewing its existing waste management practices with the aim of creating a new, responsive waste-to-resource system for introduction by early 2019 [5]. BCC collects and disposes of just under 500,000 tonnes of municipal waste each year. It collects waste from households and some business premises, as well as providing street cleaning and recycling services. Waste that cannot be recycled is incinerated in a purpose-built plant, which generates electricity for sale to the national power grid. Since January 1994, the incinerator has been operated by Veolia Environmental Services Birmingham (VESB) – an international recycling and waste management company – via a 25-year contract, which comes to an end in January 2019.

Development of new, integrated waste management systems must take account of existing infrastructure. The current environment in cities around the issue of waste is one where there are: large sunk costs relating to capital items such as recycling plants and waste collection vehicle fleets; long life-cycles for equipment such as energy from waste plants; and shortages of public sector investment. All of these preclude starting the development of integrated waste management systems with a 'clean sheet of paper'; instead, a better understanding of the existing processes is required, to provide a basis for identifying feasible opportunities to progress [6]. To stand a chance of being implemented, these opportunities must translate to business models with attractive value/cost ratios: funding will only be available for cases where investors can see how they are going to earn a satisfactory return, and the costs of implementation are not unacceptably high.

It is clear therefore, that objective and repeatable models of existing waste management systems are required to help with the design and development of new ones: objective in the sense that data used to build the model will be drawn from documents that can be referenced, rather than relying on potentially subjective input from domain experts; and, repeatable in the sense that separate teams of modellers of equal competence will produce similar models. A novel methodology for creating such models was developed and successfully applied on an earlier EPSRC-funded project, with the aim of creating models of systems-of-interest relating to the UK's railway infrastructure [7]. The methodology goes beyond modelling the high-level interdependencies identified by much of the existing work on infrastructure resilience [8]. Instead, it is based on the realisation that its context is a world made up of 'organised' or designed sub-systems (waste management, water supply, transport, food supply, etc.), which operate together as a dynamic system-of-systems whose behaviour continues to evolve over time, rather than remaining static according to some original, holistic plan. System-of-system complexity coupled with this evolutionary behaviour mean that often it isn't clear what interfaces, and therefore interdependencies, there are between the sub-systems. To overcome this problem the methodology 'reverse engineers' each sub-system using the techniques of applied systems engineering normally associated with the design of new products (cars, planes, mobile phones, etc.).

The research described in this paper has been funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) [9] and the Economic and Social Sciences Research Council (ESRC), in a joint venture project called iBUILD (Infrastructure BUsiness models, valuation and Innovation for Local Delivery). It addresses the question of whether a modelling methodology that was designed for, and performed satisfactorily in, a highly systematised business such as rail, can perform equally well in a business where the systems approach is less obvious. The methodology is based on systems engineering techniques, with which the railway's strong systems ethos aligns well. Compared to railways, however, current waste management systems appear more straightforward and to have less of a clearly documented systems ethos. The paper describes in outline the development and application of the modelling methodology in the rail context. It then describes application of the methodology to solid waste management systems in the context of Birmingham. Results from the two applications are compared and conclusions drawn as to the feasibility of applying the methodology to solid waste management. The paper finishes with some observations on future research opportunities.

Supporting Railway Innovation: Modelling the System of Interest

An earlier EPSRC-funded research project [7] explored development of a methodology for modelling railway systems-of-interest, with the aim of helping to facilitate railway innovation. Railways are complex and closely coupled systems, which can make it difficult to identify both innovation opportunities and their potential impact, once implemented, on the wider system. System models can help overcome these problems by providing a foundation from which to generate and test innovative ideas.

Model building requires: a clear definition of the boundary of the system-of-interest being modelled; elicitation, from an objective source, of the system data needed to build the model; and, integration of the system data to create a visually-realisable model. Moreover, the modelling methodology must be objective and repeatable if it is to result in the production of accurate models, as described earlier.

The methodology met the requirement for objectivity by using high-level railway technical standards as the source of data for model building. The repeatability requirement was met through the development of a systematic process for: searching the online repository of technical standards, to identify those relevant to the system of interest; eliciting system data from those standards; and, combining that data to create the model. This approach also satisfied the requirement for system boundary definition through the identification of a discrete suite of standards covering the system of interest. The model was created by integrating the data using CORE, a system modelling tool produced by Vitech Corporation in the USA, for which the project had an academic licence. The functionality of the methodology was proved by modelling one of the railway's sub-systems

The modelling process started by identifying those standards applicable to the system of interest using the systematic search process shown in Figure 1. The standards database was searched using a word, or phrase, strongly associated with the system of interest to identify what are termed the key standard(s); for simplicity, Figure 1 assumes one key standard has been found, numbered 1. The key standard's references are identified (2, 3 and 4 in the diagram). The references for those standards are then in-turn identified (2, 5, 6 and 7); this is termed the 'first iteration'. Not all of the standards emerging from the boundary definition process result in further iterations: for example, standard 2 in the first iteration is a repeat of an earlier standard; engineering judgement is used to conclude that standard 5 is not relevant to the system-of-interest, and; standard 3 does not have any references. In each of those cases the relevant arm of the diagram can be terminated. Further iterations of the process are made until all of the branches are terminated, at which point the suite of standards describing the system-of-interest includes all those in the diagram, except those at the end of tree branches.

Once the suite of standards had been identified, the task of eliciting the system data and integrating it to create the system model started. Data elicited from standards included: requirements; functions (both individual and linked together to create function threads or processes); components; inputs; and, outputs. Collectively, these are referred to as entities, that is, the things that go to make up the system. The entities were linked by relationships, as indicated in the schema shown in Figure 2, to create the integrated model. Entities in the model can be elaborated on by the application of attributes.

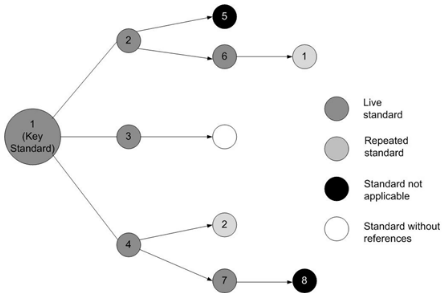

Figure 1: Diagrammatic Representation of the System Boundary Definition Process

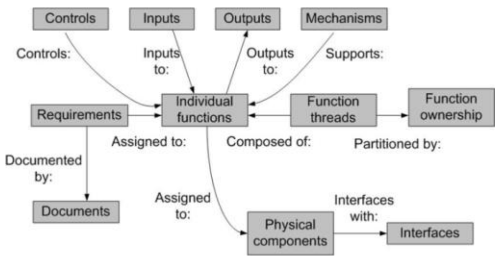

Figure 2: Indicative Diagram of an Entity-Attribute-Relationship Database Schema (Attributes not shown)

Application of the Modelling Methodology to Solid Waste Management Systems

No publically-accessible repository of waste management, system-related documentation, of the type available for the rail study, was found; therefore, iBUILD's research explored the feasibility of identifying the discrete suite of system documents by applying the systematic document search process, through the medium of Google, to the web. The document search was pursued 'top-down', looking initially at the solid waste management system as a whole, before going on to consider parts of the system in more detail.

The search terms 'Birmingham City Council', 'waste management' and 'pdf' were used in the initial search. These resulted in two key documents: the 'Birmingham Total Waste Strategy 2011' [10] and the 'Refresh of the Municipal Waste Strategy' [11]. Both of these documents were reviewed and references to other documents identified to generate the 1st level reference documents. The document search process has not yet been completed; however, it has been carried through to generate the 5th level references, at which point only nine branches of the document 'tree' remain 'live' (i.e. have the potential to generate further references). The search identified 62 relevant documents, consisting of 28 from policy and strategy, 33 from legislation and 1 master plan. The search failed to find any publically available documents describing BCC's internal waste disposal procedures, or indeed any reference to such documents. BCC confirmed that restricted-access procedural documents do exist, and supplied examples to the authors for modelling purposes.

Data for model construction is being elicited from the documents identified in the document search process. The data are stored in CORE's engineering repository and linked together using relationships to create the integrated model. An example output from the integration process is shown as the enhanced functional flow block diagram of Figure 3. To the left-hand side of the diagram are the activities generating waste. The waste forms the input to the waste management system, which in turn produces outputs such as energy, paper, glass, etc. These outputs become the inputs for the industries that re-process the recycled materials.

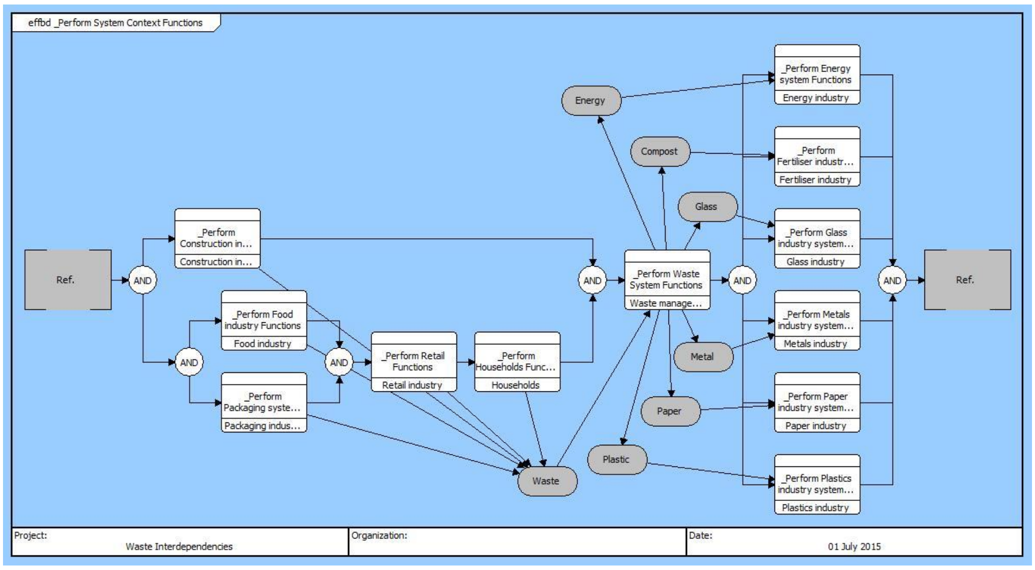

Figure 3: Enhanced functional flow block diagram showing the 'system of systems' view of solid waste management in Birmingham

Requirements have not yet been added into the model. However, preliminary research has shown that it can be difficult to elicit good requirements from documents covering policy and strategy that have not been written as requirement specifications. The language in the documents is often conditional, using words such as 'should' instead of 'shall', or describing something as very important, rather than stating that it must be included in the system design.

Discussion

The process for identifying the discrete suite of system documents appears to work for the documentation covering solid waste management. The web search, together with reading through the results to identify the references, is a time-consuming process with a higher risk of missing important links than in cases where system engineering is embedded in the process. The web search also brings up many superseded documents, and traceability of documents sometimes breaks down – for example, a master plan published in 2010 will not reference a revised version published in 2014. Detective work is required to get around both these problems, aided by the web, which, at least in theory, provides the network necessary to pull in all the potentially relevant documents.

The document search showed a disconnect between higher level documents, covering legislation, policy and strategy, and more detailed documents describing operational processes – for example, the web-based search process failed to identify links between BCC's strategy documents and their operational documents describing their various waste collection processes. Instead, these were identified as a result of meetings with BCC staff. In one respect this is not surprising, since these operations are confidential to BCC. Conversely, bearing in mind that design of the operations will have been driven by legislative/policy/strategy documents, more evidence of the connection between the two might have been expected.

When it comes to data elicitation, more work is required on the part of the modeller to elicit the system data than was the case for the railway standards. Data elicitation is also more time consuming than was the case with the railway standards, which clearly state requirements. Many of the waste documents are not technical, and therefore are written in layperson's English. System data, such as requirements and functions, are therefore often buried in text and can be difficult to identify.

The research has found that the application of systems engineering techniques to waste management in cities appears to be new. Consequently, there is likely to be a natural suspicion among policy makers and domain experts about the value of applying them until the efficacy of such an approach can be demonstrated. That said, there is clearly a need to put city infrastructures into the system model to help reveal the (multiple) opportunities for system improvement and novel business model creation. Hopefully, the research can make a significant contribution to promoting further work and progress in this area.

Suggestions for Further Research and Developments in Practice

Firstly, the work on Birmingham's waste management system needs to be taken through to its conclusion to provide a complete picture of system modelling in that environment. However, based on research carried out so far, a number of areas for future research can be identified:

- Elicitation of system data from policy, strategy and legislative documents is an important part of the modelling methodology. However, these documents are not written with system modelling in mind. More work is required to help modellers ensure they collect all the relevant data, and work is also required to explore the feasibility of changing the style of these documents in a way that would help modellers, while at the same time ensuring that they still remain accessible to the layperson. Making explicit the benefits of this would help.

- The level of granularity required in models is a big issue: too little and their contribution to the design of new systems will be limited; too much and they become expensive to build and maintain. Research is required into what the optimum level of granularity might be.

- Many of today's city systems are open and have an important interface between the organised complexity of the designed, technical system, and the disorganised complexity of the emergent behaviour of the citizenry. At the moment, however, design of infrastructure tends to view the systems as being relatively closed. Research is required to overcome this and integrate organised and disorganised complexity.

- Waste management is but one of many city systems that all should act in harmony to serve citizens. Moreover, in general these systems are interdependent, and these interdependencies offer the potential for economic, social and environmental benefits to be gained via their intelligent synthesis. This potential needs to be explored.

- Application of applied systems engineering techniques and reverse engineering to city systems appears to be relatively new. There is a need, therefore, for research to help demonstrate to decision-makers, system managers and domain experts the considerable benefits that a systems approach can bring.

Conclusions

As the world's population increases cities are under pressure to develop ever-more effective and efficient city infrastructure systems, such as waste management, that will contribute to a more sustainable and resilient future. These systems may appear straightforward, but are complex both in terms of the technology involved and, particularly, the interface that they have with the people living in the city. System models offer a way of coping with that complexity and helping policy makers, managers and domain experts to develop the new systems that will be required.

This paper has shown that a methodology developed originally to create models of railway sub-systems, can be applied successfully to city waste management systems. The methodology is in the process of being applied to the waste management system in the City of Birmingham, UK, to provide the baseline, virtual test bed and framework required to support future development. The research has demonstrated that models can be built using data elicited from policy, strategy and legislative documents. The research is on-going and, it is hoped, will contribute further to the development of Birmingham's future waste management system.

Actions to improve the application of the methodology have been identified in the form of future research and practice. In particular, there is a need to: demonstrate the efficacy of systems engineering to city service provision and explore with authors of policy, strategy and legislative documents how to improve data elicitation; research the optimum level of granularity to which models should be developed; improve integration of the technical and human in open complex systems; explore, synthesise and exploit the interdependencies between the numerous city systems; and, investigate how best to improve the uptake of systems engineering techniques among city policy makers, managers and domain experts.

Acknowledgements

This work has been funded by the UK Engineering and Physical Sciences Research Council and the Economic and Social Sciences Research Council (iBUILD Grant Ref.

EP/K012398/1). The authors are grateful to the Vitech Corporation, Blacksburg, Virginia, USA for providing an academic licence for CORE, together with technical support. The authors are equally grateful for the help received from staff at Birmingham City Council, Fleet and Waste Management

References

1. UNEP, 2013, 'Guidelines for National Waste Management Strategies: Moving from Challenges to Opportunities', United Nations Environment Programme, Nairobi, Kenya
2. European Commission, 2010, 'Being wise with waste: the EU's approach to waste management', Environment Directorate General, Brussels, Belgium
3. European Commission, 2010, 'Life Cycle Thinking and assessment for Waste Management', Environment Directorate General, Brussels, Belgium
4. McDougall, F. R., White, P. R., Franke, M., Hindle, P., 2001, 'Integrated Solid Waste Management: A Life Cycle Inventory', 2nd Edition, Blackwell Science, Oxford, England
5. Birmingham City Council, 2014, 'From Waste to Resource: A Sustainable Strategy for 2019', A Report of the Transport, Connectivity & Sustainability Overview and Scrutiny Committee, Birmingham City Council
6. Murray, R., 1999, 'Creating Wealth from Waste', Demos, London
7. Bouch, C., Roberts, C., 2013, 'Developing System Models to Help Great Britain's Railways Embrace Innovative Technologies with Confidence', Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit, Volume 227, Issue 6, pp 677-684.
8. Rinaldi, S.M., Perrenboom, J.P., Kelly, T.K., 2001, 'Identifying, Understanding and Analyzing Critical Infrastructure Interdependencies', IEEE Control Systems Magazine, December 2001
9. EPSRC, 2013, 'i-BUILD: Infrastructure BUsiness models, valuation and Innovation for Local Delivery', Engineering and Physical Sciences Research Council (EPSRC), Grant EP/K012398/1,
10. SKM Enviros, 2011, 'Birmingham Total Waste Strategy – Final Report', Report for Birmingham City Council, SKM Enviros, Manchester, UK
11. Birmingham City Council, 2012, 'Refresh of the Municipal Waste Management Strategy', Report of the Transport, Environment and Regeneration Overview and Scrutiny Committee, Birmingham