Infrastructure modelling 2.0

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Abstract: To support stakeholders involved in infrastructure development, we develop evolutionary models of these complex systems, which is a formidable task with respect to data requirements, information representation and knowledge management. Re-addressing a case on bio-electricity infrastructure evolution, we demonstrate first a series of visualisations of economic and ecologic system parameters as they change during infrastructure development over simulated decades. This setup allows us to demonstrate to stakeholders a means to anticipate the consequences of decisions on (dis)investment of power generation options available.

In developing these tools, our approach needed to be expanded to better handle the complexity of infrastructure systems, due to the multiple relevant social and technical contexts from which these systems need to be considered. The second part of this paper describes our work on enabling collaborative mapping of our knowledge of infrastructure systems to help integrate diverse types of knowledge. Current internet-enabled developments such as Web 2.0 and the Semantic Web offer tremendous scope to lower the transaction cost of gathering and assembling data. Already, these are changing the ways scientific collaboration is conducted. Finally, we suggest to connect this to evolutionary models to elucidate the dynamics of these systems.

Keywords: agent-based modelling; ABM; complexity; bio-electricity; infrastructures; information technology.


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1 Introduction

Energy infrastructures are an integral part of sustainability. First, in a narrower sense, we have deemed that they are critical for the functioning of our society and economy, and are thus crucial for the sustainability of ourselves and our living standards. Second, these are the types of infrastructures that we do not only intend to persist in the future, but that are also likely to persist because of natural monopoly, network effects and lock-in. They must be accessible, affordable and reliable for end users who have come to be dependent upon them. Third, these systems represent the primary means to cope with issues of global sustainability that go beyond the scope of day-to-day accessibility, affordability and reliability. Today, in industrialised countries, in excess of 90% of our energy needs is met by fossil fuels that are taken from an inevitably dwindling resource base. Fossil fuels inevitably are converted to CO$_2$, which, through its increasing concentrations in the atmosphere, threatens global climate stability and is anticipated to cause an average global warming between 1.1°C and 6.4°C (IPCC, 2007).

Addressing long-term sustainability of energy infrastructures is challenging since we want to have these systems to continue delivering their services without interruption. At the same time, we recognise that the means by which we produce these services must change as evidenced by statements made by world leaders who vouched to reduce CO$_2$ emission by 20%, 30% or even 80% (European Parliament, 2009) in the span of a lifetime. To avoid a system collapse requires a dramatic and timely transformation of our energy infrastructure systems in fuel diet, technologies used, system components, system structure, stakeholders involved, governance, policy and regulation, etc. As of late, this has been the subject of transition studies and transition management (Chappin and Dijkema, 2009).

We have set out to model transitions as also described in this issue by Chappin and Dijkema (2009), Nikolic et al. (2009) and elsewhere by Davis et al. (2009). To support stakeholders involved in infrastructure development, we develop evolutionary models of these complex systems. Decomposing them as sociotechnical systems reveals, however, that this is a formidable task with respect to data requirements, information representation and knowledge management. To deal with these challenges, we believe that there needs to be a transition to a type of ‘infrastructure modelling 2.0’ that leverages developments occurring in the realm of the semantic web which aims to improve how we manage data, information and knowledge.

In this paper, we present a way forward to tackle these tasks by addressing the following two questions:

1 How can we represent information on aggregated simulated infrastructure characteristics to stakeholders?

2 How can we cope with exploding data requirements needed to represent complex systems?
The paper is organised as follows: In Section 2, the sociotechnical systems approach is summarised and embedded with complex system theory. Sustainability is defined and related to life cycle assessment. Essentials of Agent-Based Modelling (ABM) are given. Section 3 focuses on the information presentation problems encountered in the bio-electricity case which has been described in more detail by Davis (2007) and Davis et al. (2009). In Section 4, the solutions developed in the course of this case study through visualisation techniques are given and reflected upon. In Section 5, the second question is addressed. Discussing and combining recent developments in Information and Communications Technology (ICT), the sustainability challenge, complex systems and knowledge representation lead to initial directions on how to methodologically underpin and enable the collaborative mapping of our knowledge of infrastructure systems and combine if not leverage, these with the inventorying of and accessing the data sources online. Finally, in Section 6, conclusions are drawn on the implications and outlook for this further evolution of modelling tools.

2 Foundations

As humans, we face a dilemma where gradual social and technological advances over the past centuries have created a global system of enormous complexity. From the recent financial crisis, it is clear that systems such as the global economy cannot be centrally controlled and, if not, it may already soon be impossible to centrally conceptualise them any longer (Allenby, 2007). Complexity is part of our everyday life and understanding it and dealing with it are imperative.

This complexity has a direct impact on the sociotechnical systems that enable our current lifestyles. We have moved beyond a problem of optimisation into one the scale of which we have never dealt with before. We are playing catch up as we realise the magnitude and nature of what we have collectively created with these sociotechnical systems supplying our needs. Change is certain and transitions will happen whether or not we are ready for them.

2.1 Sustainable systems

In order to transition towards sustainable systems, we must be able to create a suitable abstraction of reality that allows us to understand how these systems work in the first place. This can be difficult as sustainability is multifaceted and relevant to many different disciplines. Research on how this may be achieved can be found starting with the advent of general systems theory (Boulding, 1956). This field of research recognises that while many disciplines deal with systems, they often do not share a common language. Because of this, communication across multiple disciplines can be difficult or impossible even though they may be dealing with similar types of phenomena.

In developing a common language for systems, we need to know what a system is. Asbjørnsen (1992) defines a system as a:

"structured assemblage of elements and subsystems, which interact through interfaces. The interaction occurs between system elements and between the system and its environment. The elements and their interactions constitute a total system, which satisfies functional, operational, and physical
characteristics, as defined by the user and customer needs and requirements, over a defined total system life cycle of the system existence, including the life cycle of bringing the system into being.”

Others such as Blanchard and Fabrycky (1998) differentiate a system from randomness by stating that systems are composed of components, attributes and relationships that work together towards a common objective or purpose.

In science and engineering, the object of study and design is a physical system or technical artefact or installation. Traditionally, system theory and design methods have been developed therein which are used to break the system down into its smallest constituting parts. For example, power plants may be broken down to their individual unit operations or equipment items; an innovation system is broken down into the types of organisations that take part in it (Heckert et al., 2007). Furthermore, a sociotechnical system can be thought to be a system decomposed into technical and social networked subsystems (Herder and Thissen, 2009; Herder et al., 2008; Dijkema and Basson, 2009).

When we now move to infrastructures, we see that they have both technical and social subsystems that interact and shape each other. History teaches us, however, that energy infrastructures were not completed as a one-off grand design, but rather they evolved and grew over decades. The Dutch power grid, for example, grew out of a number of local networks that subsequently became interconnected by a national grid which, in turn, expanded over decades both in geographic coverage and capacity. While there existed a series of long-term master plans for a few decades (De Vries, 2004), the system grew and developed as a series of individual projects such as power plants, transmission lines, etc. In each of these, stakeholders involved had different interests, hence different priorities and, often, different power. When the sector was liberalised and deregulated, Kuit (2002) suggested that the social network was continuously engaged in infrastratego, a strategic gaming. Energy infrastructure systems thus grow and evolve with time. Each and every decision adds to determining its future path based on path dependency and lock-in of the growth trajectory.

Elsewhere, we have extensively argued that this is a complex adaptive system (Nikolic et al., 2009; Davis et al., 2009) which cannot be engineered top-down. Rather, they need to be kicked around, pushed or driven in the right direction using suitable instruments. These not only include legal and regulatory systems (e.g., Chappin et al., 2009), investment and innovation subsidies, but also communication, debate, etc. So, only parts of the system get decided upon and engineered top-down, but the system, as a whole, assembles through the actions (which may be more or less coordinated) of stakeholders involved who each exhibit a unique response to incidents, trends and opportunities.

Any system has a system boundary, which in modelling or managing it, defines the boundary between the object control and the external world influencing it. Seriously adopting the sociotechnical systems perspective as the system idea for infrastructures implies an immense system scope which relates to a vast realm of knowledge domains, theories and tools to be used and integrated when we want to construct models. At the same time, we must understand “the real challenge posed by the systems idea: its message is not that in order to be rational we need to be omniscient but, rather, that we must learn to deal critically with the fact that we never are” (Ulrich, 1988; Ryan, 2008). So, even given this vast scope, we still must limit ourselves if only to deal with limited time, data, information and knowledge.
In this paper, we are concerned about achieving sustainable development of energy infrastructure systems. Sustainable development is defined by Brundtland (1987) as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In business circles, it is often known by the mantra ‘people, planet and profit’ by which it is suggested that we strive to maximise the benefits realised for each of these concerns. Moreover, it suggests an interdependency of system elements and system characteristics; in reality, however, sustainability cannot be achieved by maximising only one aspect because it is an emergent property of the overall system. Indeed, it does not make sense to talk of a single entity as being sustainable by itself since it operates within and is dependent on a larger system (Allenby, 1999).

Grasping the meaning of sustainability means that we must employ a systems approach. To help understand systems, we develop tools that allow us to capture elements of it. Two of these tools, ABM and life cycle analysis, are discussed below with regard to the types of approaches they use.

### 2.2 Agent-based modelling

The concept of representing elements of a system as individual agents is central to ABM. However, as ABM is used in very diverse scientific fields, there is no exact definition of it. One explanation is given by Shalizi (2006) who states that:

“an agent is a persistent thing which has some state we find worth representing, and which interacts with other agents, mutually modifying each others’ states. The components of an agent-based model are a collection of agents and their states, the rules governing the interactions of the agents, and the environment within which they live.”

Shalizi’s definition can be seen as also encapsulating the definition of Asbjørnsen (1992) who, as stated in the previous subsection, defines a system as a “structured assemblage of elements and subsystems”. In our models, agents are built to represent these elements which then form the structure of subsystems. In these models, when these agents interact with each other, they form networks which can then give rise to complex systems. For the ABM in this paper, agents must trade in order to buy raw materials and sell their products. Agents are only limited in that they must find a suitable trading partner who makes a feedstock that they need or is willing to buy what they produce. If an agent is not profitable, then it is removed from the simulation. The decision-making rules specified for the agents will then generate the overall system structure that emerges.

Essentially, we are able to grow self-assembling structures of supply chains that are controlled by agents who make strategic and operational decisions based on the economic and environmental performance of their technological installations. Agents can be viewed as companies that own technologies. Over time, some technologies may not be profitable and go out of business while others are added as new investments are made. Since agents necessarily trade with each other, their decisions do have an economic impact on other agents in the simulation.

### 2.3 Life cycle analysis

Life Cycle Assessment (LCA) is a core method that provides an important system metric. LCA is a tool used to analyse:
“the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal.” (Guinee, 2002)

This comes from a recognition that environmental problems are systematic in nature and that by choosing one particular product or service, we are indirectly supporting environmental impacts that may occur several stages away from us in the supply chain. For example, this allows us to take a product unit such as 1 kWh of electricity and to examine the total CO$_2$ emissions resulting from fuel extraction, transportation and final conversion of the fuel into electricity. Depending on the type of investigation, additional processes could be added to the analysis such as the production of capital goods and the raw resources needed in their manufacture.

As we have argued elsewhere (Davis et al., 2009):

“The idea behind LCA is very powerful, although as we try to tackle larger and more complex problems, its limitations become more apparent. In its current implementation, it views the world as being composed of static connections between technologies. It is also a linear model in that if production of one good is increased, the flows of the upstream technologies are scaled proportionally as well.”

While this tool can be very useful in the correct context, it does run into limits when evaluating complex systems. Essentially, it is a tool for analysing material flow networks and identifying problems, but it will not necessarily tell how to fix the problem. For instance, the modelling of interconnected metal cycles is problematic since metals that participate in linked cycles cannot be analysed independently. This is due to different metals that may originate in the same ore or be combined later in alloys. Due to feedback loops and time delays in these interlinked metal cycles, a change in one element of the system will impact the material flows in the rest of the system (Verhoef et al., 2004).

In the next section, a case study on bio-electricity will be briefly described to illustrate the types of issues that we have investigated using the perspective and tools described above.

3 Case study: bio-electricity

Concerns over climate change and the security of future energy supplies have led to an increased focus on utilising biomass as a feedstock for energy production. While many want to see biomass succeed for all the right reasons, it has become clear that not all biomass is suitable, and we have to be conscious about not creating new problems as we work to solve old ones. This has become evident in the recent controversy over the cofiring of palm oil in Dutch coal plants (Junginger and Faaij, 2005). It has become clear that the increased global demand for renewable fuel has resulted in the conversion of some Southeast Asian tropical forests into palm oil plantations (Fargione et al., 2008). Even without this complication, there are already questions about how effectively we can reduce greenhouse gas emissions when the biomass being used is shipped from the other side of the world. With interest now growing in using wood byproducts from Canada (Damen and Faaij, 2006), answering this question becomes even more critical.
Analysing this from a large-scale systems perspective is important due to the global impact of increasing greenhouse gas emissions. For a country to achieve a meaningful reduction in greenhouse gas emissions, it cannot reduce emissions inside its borders while its economic activity leads to increasing emissions outside its borders. Addressing this means that at every step in the energy supply chain, an accounting needs to record environmental and economic flows taking the form of materials, energy, emissions and other environmental impacts. In an LCA, these results can then be aggregated to show the total flows and impacts resulting from the production of a functional unit such as 1 kWh of electricity.

The feedstocks and technologies investigated are shown in Table 1. What is interesting is that each feedstock and production method has different strengths and weaknesses. Each of them has a defined lifetime and may also only be viable at certain scales.

<table>
<thead>
<tr>
<th>Biomass feedstocks</th>
<th>Bio-electricity production methods</th>
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<tbody>
<tr>
<td>Demolition wood</td>
<td>Cofiring with coal</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>Gasification</td>
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<tr>
<td>Wood chips</td>
<td>Combined heat and power</td>
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<tr>
<td>Refuse derived fuel</td>
<td>Anaerobic digestion</td>
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<tr>
<td>Manure</td>
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<td>Palm oil</td>
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<td>Rapeseed oil</td>
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An ABM was used to represent the evolving bio-electricity infrastructure. At each simulation interval, this consisted of a portfolio of interconnected generation options which took in certain feedstocks and generated electricity. All these physical flows were arranged via contracts. To establish these contracts, bidding and negotiating between agents took place, thereby emulating the Amsterdam Power Exchange (APX) and acquiring fuel against market prices.

Using the system state – structure, content and operation – each time step in LCA was computed. This was done by connecting the ABM with the LCA through suitable mapping of their respective data structures. Effectively, where the state of the ABM represents the system, connection with an LCA database allowed automatic assembly of the life cycle supply chains supporting and enabling that system from which the LCA impact can then be computed. Many of the agents defined were able to use different types of feedstocks in order to make electricity and evaluate their choice of feedstock based on information about LCA impact and profitability. A more detailed description, background and implementation is given by Davis et al. (2009) and Davis (2007).

4 Modelling and visualisation

Building upon general system engineering and modelling principles, we will now discuss several of the tools we have used for modelling and understanding systems. Figure 1 briefly illustrates the approach used for the case study described in the previous section.
First, a system is conceptualised into a model through the use of an ontology which helps structure information. Information stored in the ontology is then used as input for our modelling software. Model data is then interpreted through visualisation techniques, the results of which are then given as feedback on how we interpret real systems and further develop the model. The models we develop can be seen as having multiple types of inputs and outputs due to the complexity of the systems we investigate. Due to the complexity of the systems modelled, it is important that the results be viewed from multiple perspectives and by multiple stakeholders and domain experts.

**Figure 1** Illustration of aspects of the modelling process (see online version for colours)

4.1 **Ontology**

To help structure information in our models, we use an ontology which is a framework for representing relationships based on *classes*, *instances* and *properties*. A *class* represents the data structure that will exist for a particular type of concept. For example, we define a *technology* class which tells us the types of information we can expect to exist for every type of technology we define. Every type of technology we define will be specified to have *properties* related to its materials, inputs and outputs along with other data such as fixed operating costs and expected physical lifetime of the installation. An *instance* of a technology will represent an actual physical instance of a technology such as a specific coal burning power plant at a certain location.

A further implication of using an ontology is that it allows us to connect diverse types of properties to an agent. This may allow an agent to exist in several different types of networks simultaneously such as networks of material flows, economics flows or even social connections. This aids in data collection during a simulation and can allow us to view the evolution of the system based on different types of perspectives and indicators.

The ontology we use has been developed over several years (van Dam, 2009; Nikolic, 2009) and has significantly aided our modelling efforts as it allows reuse of existing concepts and data structures, thus saving on development time. As will be discussed in the last section of this paper, trends are occurring which allow for new types of benefits to be realised through the use of ontologies, and we are actively exploring these.
4.2 Model visualisation

We have found visualisation to be a useful technique due to the nature of the modelling process as it helps increase transparency of model operation and results. Visualisation can be perceived as an art where we try to present the maximum amount of relevant information to the user without cognitively overloading them. In creating a model, we are often interested in seeing how individual types of behaviour can propagate throughout a system and, in turn, influence the decision making of other agents. This means that we need to be able to examine information over multiple levels, stretching from an individual to an aggregate system view. Additionally, we are interested in understanding the distributions inherent in data generated from a model. In other words, we are not just interested in averages but also in the outliers. For example, the averages may tell what a model ‘normally’ will do, while outliers could expose errors in programming or even rare unforeseen events that may occur in reality.

The challenge in visualising dynamic evolving systems lies not necessarily in the volume of data but in dealing with the specific contexts and meanings of the different types of data. For example, one may find that aggregating monetary flows gives a decent indicator of system behaviour. However, attempting this with mass flows requires caution since a kilogram of platinum is not equivalent to a kilogram of sand. Additionally, mapping flows across agents can be difficult since, as Blanchard and Fabrycky (1998) state, “A common system function is that of altering material, energy, or information.” Any time one of these is altered, the context may change so that it is not directly comparable to its original form.

In order to properly evaluate models, we need to have visualisation techniques that are able to show multiple facets of model operation. This often involves analysing data present at a single time step, multiple time steps and across multiple model runs using different input parameters. For example, the network structure formed by the agents can be seen at every time step or this view can be animated to show the evolving network structures over time. We are also interested in seeing trends present in the population of agents such as how money is distributed over time. At an even high level, we are interested in how these trends then vary between distinct simulation runs with different input parameters.

Several of the types of visualisations we created are shown below. In Figure 2, we show a graph illustrating the material and economic flows between different actors. Understanding the topology of interactions can be important as it can give an indication of the role of an agent in the system. For instance, this type of visualisation could show that a particular agent provides the only pathway for converting some raw resource into another resource used by many other agents, thus indicating that its existence is quite important for the success of the other agents as well. Figure 3 is a stacked graph showing the assets of agents over time in a single simulation run. Each stripe represents a single agent, with the height indicating its relative assets. During the simulation, agents are removed and added which explains why some stripes appear and disappear. Negative values are plotted ‘upside down’ below the main line. What we see here is that the distribution of assets changes over the course of the simulation. At the beginning, a few agents have large assets, although as the simulation continues, there are many more agents who have proportionally smaller assets. Figure 4 is a dynamic visualisation conducted throughout the simulation showing the flows between agents at the current simulation time step. The small charts around the circumference represent profits and
assets for individual agents and provide a quick way to ascertain the state of the system. Finally, Figure 5 illustrates results for a parameter sweep. Higher values represent more reductions in CO$_2$ emissions. Each intersection of lines represents a simulation run with a particular combination of parameters as indicated by the two horizontal axes. For instance, we can see from this graph that varying the type of decision making has little effect on the results, while varying the tax rate has a large influence at certain values.

**Figure 2** Network graph showing material and economic flows between different actors in the bio-electricity case study

Note: From this, we can see that the distribution of assets changes over time.

**Figure 3** Visualisation showing the assets of agents over time in a single simulation run (see online version for colours)
Figure 4  Visualisation showing economic and material flows between agents (see online version for colours)

Note: The small charts around the circumference represent profits and assets for individual agents.

Figure 5  Visualisation showing the results of a parameter sweep over a combination of agents, decision-making types and different tax rates (see online version for colours)
4.3 Reflection

What we have created through our existing work is a means to convert conceptualisations about systems into models that can generate complex behaviour similar to real world patterns. This allows us to test out different scenarios and characterise how these systems will perform under various assumptions. Through the use of an ontology, we can model agents possessing information and data that are relevant in different contexts. These agents can then interpret this information and adjust their behaviour based on predefined rules. This behaviour then influences the overall system behaviour as the interaction of agents with each other has propagating effects. Through visualisation techniques, we have been able to better understand and communicate the working of models.

5 New directions

In developing these kinds of models and techniques further, we will face challenges related to transparency, expressibility and knowledge management. Transparency has been mentioned above in relation to the use of visualisation techniques, although it goes beyond just the use of that tool. For model development and presentation of results, transparency is crucial for answering the ‘what happened and why’ questions. We need to be able to clearly understand how the code behind the model works and be able to illustrate how these mechanisms can result in the overall model behaviour. As a central theme, it is crucial in facilitating collaboration and in discussing the success of the open source software movement. Raymond (2001) has stated that “given enough eyeballs, all bugs are shallow”. The ‘bugs’ we deal with are not just in software but exhibit themselves in the real world problems we try to solve.

Expressibility is an issue since we have to formalise concepts that are described in natural language (i.e., what you are reading now). For example, the Oxford English Dictionary contains over 170,000 words in current use (Oxford University Press, 2009). By the sheer size of vocabulary, it is clear that the formalisation process can be difficult, even without considering techniques such as analogies which can compress large amounts of information into a single sentence, and while recognising that even while using natural language, people can often disagree about how to represent concepts.

The issue of knowledge management relates to how we integrate, connect and reuse information. This will be described much further in the next section and will focus on the fact that embracing a systems view means that we must deal critically with the fact that we cannot be omniscient about systems (Ulrich, 1988; Ryan, 2008). While we cannot be omniscient, we are finding better ways to aggregate information and foster a collaborative exploring of complex systems.

5.1 Challenges for sustainability

The study of sustainability is maturing and we are figuring out how to ask better questions to create better solutions. Some even suggest that these questions will take the form of querying complex systems (Allenby, 2006). To an extent, this is already starting to happen. One of the challenges in dealing with complex systems lies in the multiple formalisms that are used to describe them. While it is impossible to contain these within a
single ontology, work is being done on making connections between domain-specific ontologies and higher-level ontologies. Much of this is happening within the field of systems biology (Kitano, 2002) where there is a desire to take a true systems view stretching from molecules to metabolic pathways to outward physical characteristics.

This goes beyond just identifying linkages and is more about understanding the context, constraints and environment within which our infrastructures operate. While tools such as LCA have provided a significant start, some such as Kay (2002) go on to say that understanding the sustainability of systems will entail that:

“[…] the self-organizing behaviors of the system need to be identified, described, and understood insofar as is possible. This involves identifying the attractors accessible to the system, the feedbacks which maintain the system at the attractors, the external influences which define the context for a specific attractor, and conditions under which flips between attractors are likely.”

From this, we see that understanding sustainability requires the realisation that it is an emergent property of a system (Allenby, 1999). We must do more than create a static system description, but rather, we must be able to elucidate the dynamics that are possible. These dynamics can occur on multiple levels, ranging from the level of individual system actors to the overall aggregate behaviour of the system.

5.2 Collectively mapping complexity

Real world systems are made up of linkages created by different people and we need to create models of systems in the same fashion. We need to leverage network effects where the contribution of knowledge leads to accumulating benefits to additional users. To an extent, the foundation for this has been laid already, although there is still an opportunity to create a greater diversity of models.

Inherent in many discussions of sustainability is the idea of connectedness as exemplified in LCA where we try to determine how much of a system-wide impact can be attributed to the production of a single good or service. To an extent, this has a parallel in the famed butterfly effect proposed by Lorenz (1972) where it was suggested that a butterfly flapping its wings can, through a series of events, cause a tornado far away. On one hand, this is a thought experiment illustrating an extreme example of tracing causality. However, when we do trace chains of causality, it is not unusual to find examples such as studies reporting that sourcing biofuels from certain palm oil plantations results in higher CO$_2$ emissions than fossil fuels (Fargione et al., 2008) which is not necessarily intuitive. While Lorenz was talking about the chaotic patterns in weather systems, the important point is that there will always be an element of uncertainty in many systems due to the inherent connections between elements, and we need to be aware of what we do not know and why. At the minimum, we need to get better at mapping the pathways by which events in systems can propagate and contribute to overall system behaviour.

As discussed below, this vision cannot be realised through a solitary endeavour. Understanding complex systems will necessarily involve not just diverse viewpoints but also tools that allow for information to be aggregated and connected in useful, meaningful ways. This will require a type of collective intelligence where collaboration will allow for the creation of a growing web of information describing knowledge and
In understanding sustainability, we need to recognise that many of the problems we face are emergent phenomena. This is clearly seen with the issue of CO₂. We are trying to break out of a state of technological lock-in which can be seen as a system attractor. This lock-in was not created by one single entity but by multiple actors over multiple geographic scales and time frames. Any solution must recognise this complexity. In describing these kind of problems, Schaltegger (1997) borrows from the economist Hayek (1945) in saying that:

“The economic problem in general, as well as that of environmental protection is [...] how to secure the best use of resources known to any of the members of society, for ends whose relative importance only these individuals know. Or to put it briefly, it is a problem of utilization of knowledge which is not given to anyone in its totality.”

Hayek (1945) goes on to say:

“The problem is precisely how to extend the span of our utilization of resources beyond the span of the control of any one mind; and therefore, how to dispense with the need of conscious control, and how to provide inducements which will make the individuals do the desirable things without anyone having to tell them what to do.”

In other words, Hayek recognises that this is really a problem of distributed collective intelligence. No one person has the entire solution. Sustainability means different things to different people, and the issue is that we are ultimately searching for something that is open ended. Sustainability is not an endpoint but a process of continuous evaluation and implementation of our goals and strategies (Boons and Berends, 2001). This is the real challenge and opportunity. People will adapt to fulfil their own needs based on the criteria and knowledge they have about their own personal situations. Top-down control is not feasible; however, bottom-up control is not a panacea either. The world is a complex adaptive system and we need to figure out how to develop better incentives and control mechanisms to steer the system in a better way. ABM is one means for us to test different theories about how to achieve this. While we cannot be omniscient, we cannot afford to be ignorant either of the consequences resulting in connections in the systems we operate.

In understanding how to harness distributed collective intelligence, we should look at the example of how economic markets work. As Hayek (1945) has said regarding the economic system, “The whole acts as one market, not because any of its members survey the whole field, but because their limited individual fields of vision sufficiently overlap so that through many intermediaries the relevant information is communicated to all.” This overlap in fields of vision is crucial. We need to foster a means for people to contribute knowledge so that there is sufficient overlapping to aid understanding of complex systems.
These ideas have been around for quite some time as people began to realise that the growth of information was exceeding our capacity to organise and navigate it. For example, Bush (1945) has criticised the artificiality of indexing systems based on hierarchical or alphabetical sorting schemes. He argues that the human mind works by association where we organise things by a web of trails connecting related types of concepts. To help organise information, he has envisioned that as people read documents, they would create associative trails through other documents, connecting similar related ideas. These trails could then be shared with other people who would additionally weave in their own trails. He went on to say that “[w]holly new forms of encyclopedias will appear, ready made with a mesh of associative trails running through them”. This statement can arguably be perceived as anticipating the creation of Wikipedia 50 years in advance.

Even he was preceded by Otlet (1934; 1990) who, by 1934, faced the reality that paper-based information systems simply are not scalable and wrote of a “mechanical, collective brain” that could be accessible through telecommunication networks. In one of Otlet’s first papers (1891), he mentioned the need to map out academic fields by going through available literature and decomposing articles into facts, interpretation of facts, statistics and sources, all in an attempt to help science move forward and avoid authors being unaware of the similar work of others (see also Otlet, 1990).

The point with these stories is not just that many of the technologies we currently take for granted were foreseen long ago, but rather that many of their visions still have yet to be realised. As described below, we are starting to realise how to facilitate this and are seeing these ideas being picked up in several scientific fields.

Central to the facilitation of collective intelligence is the lowering of transaction costs. Coase (1937) has argued that large organisations can reduce transaction costs more than a small organisation but will eventually face an upper limit based on their own bureaucracy which has been called a Coasian ceiling. However, Shirky (2008) has proposed that there is also a Coasian floor. By this, he means that, historically, there has been a set of transactions that could not be performed since it required an organisation; but no organisation was willing to bear the costs. With the advent of many of the technologies employed on the internet, the transaction costs for people organising dropped tremendously.

The ability to lower transaction costs to facilitate mass collaboration is already being utilised in several scientific fields. For example, the study of metabolic pathways is being helped by group collaboration through shared wikis and group annotation tools (Pico et al., 2008; Doerr, 2008). These tools serve as a means to aggregate individual contributions into an emerging higher-level view of their systems of interest. The intent of these projects is quite similar to what LCA researchers do in that they both examine how material and energy flows occur in different systems, although one is at the cellular level while the other is at a global scale.

This is part of a larger trend where advances in computing power are being coupled with new ways of interacting with information. What we also see is that massive amounts of real world data are being generated describing the state of our sociotechnical systems, and quite a challenge exists in handling, organising and utilising this information. The opportunity and problem of ‘big data’ (Anonymous, 2008) is being tackled by researchers turning to advanced data mining tools, online community collaboration tools and sophisticated visualisation techniques.
Some of these efforts are being pursued under the vision of the linking open data initiative (Heath, 2009) which seeks to start connecting publicly available databases both through publishing the data online and linking equivalent concepts that exist between databases. In other words, this would allow people to search for information on a single concept simultaneously in multiple databases. Already through a community effort, structured information have been retrieved from Wikipedia, allowing one to search through sets of pages simultaneously by performing queries such as find all “Soccer player[s] with tricot number 11 from club with stadium with greater than 40 000 seats born in a country with more than 10M inhabitants” (DBpedia, 2009). While this is admittedly a ridiculous type of query, the point of this discussion is that underutilised technology currently exists which allows us to query very complex types of information. Adopting this can be immensely powerful as it provides the ability to rapidly search for patterns within the data.

5.4 Semantic web technologies for modelling

In technical terms, adopting these semantic web technologies has meant, as a first step, converting our frame-based ontology to a Web Ontology Language (OWL) format. One of the advantages is that OWL is a standard which specifies a distinct Uniform Resource Identifier (URI) for every instance, class and property type contained in the ontology. This unique identifier can be specified to be a Uniform Resource Locator (URL) or, in other words, a web address. This ability allows us to take our own ontology and make links from our own information to other ontologies that are distributed across the web (Antoniou and Van Harmelen, 2008) as a sort of network of ontologies.

There is no single master ontology but instead there are different ontologies that concern topic areas that people can generally agree on. For instance, there is the Friend of a Friend (FOAF) project (Dodds, 2004) which provides a standardised data structure, i.e., vocabulary, for describing facts about people. There is also the Simple Knowledge Organization System (SKOS) (Isaac and Summers, 2008) which aims to provide a vocabulary for creating thesauri, taxonomies and other classification schemes.

Standardisation such as this is important as it enables us to more effectively search over multiple ontologies simultaneously over the internet since everyone uses the same terms to describe things. At the same time, it is impossible to standardise all terms, so people are still free to define their own terms in their ontology.

For those studying energy infrastructures, these trends are interesting as they can allow us to more efficiently aggregate large amounts of relevant information. As more data sources are made available using these types of technologies, it can help us in better identifying the opportunities and constraints that exist within a particular system. For instance, for the bio-electricity case study, it would be interesting to be able to query system information to get indicators on real world constraints on biofuel availability. Additionally, it may be found that certain countries have a more aging energy infrastructure, indicating that transitions may be easier in these locations due to a large upcoming investment cycle.
6 Conclusions

Understanding and facilitating sustainable transitions of energy infrastructures requires a systems view. Through our work towards this goal, we have shown that it is possible to approach problems of sustainability by creating models that are able to represent economic and environmental information such as through using an LCA within an ABM. Creating these models has been a learning process where we have realised that the desire to deal with complex systems leads to larger implications of how we approach the modelling process. For example, this has shown us that we must find ways to deal critically with the fact that we cannot be omniscient about systems. This involves exploring means to increase transparency, deal with issues of expressibility and incorporate context-specific knowledge from different domains.

The insight that sustainability is an emergent property of a system provides a challenge and indicates the need for us to get better at collectively mapping the systems we inhabit. From the discussion here, it appears that the development of tools needs to leverage many of the trends that are occurring where information technologies are changing the nature of scientific collaboration. As has been discussed, trends occurring in the lowering of the transaction costs for participation, increasing transparency and the interlinking of information can provide an important basis to aid future model development and decision support tools.

References


