

From Organisational Behaviour to Industrial Network Evolutions

Stimulating Sustainable Development of
Bioenergy Networks in Emerging Economies

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Declarations

I declare that the entire contents of this thesis are, to the best of my knowledge and belief, original unless otherwise acknowledged in the text. I have not submitted this, in whole or part, for another degree at this or any other institution.



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21 October 2008

Abstract

The aim of this thesis is to understand what drives the evolution of industrial networks and how such understanding can be used to stimulate sustainable development. A complex adaptive systems perspective has been adopted to analyse the complex interaction between organisational behaviour and industrial network evolution. This analysis has formed the basis for the development of a modelling approach that allows for quantitative exploration of how different organisational perceptions about current and future uncertainty affect their behaviour and therefore the network evolution. This analysis results in a set of potential evolutionary pathways for an industrial network and their associated performance in terms of sustainable development. Subsequently, this modelling approach has been used to explore the consequences of interventions in the network evolution and to identify robust interventions for stimulating sustainable development of industrial networks. The analysis, modelling approach and development of interventions has been developed in the context of a bioenergy network in the region of KwaZulu-Natal in South Africa.

Industrial networks are an important aspect of today's life and provide many goods and services to households and individuals all over the world. They consist of a large number of autonomous organisations, where some organisations contribute by transforming or transacting natural resources, such as oil, agricultural products or water, while other organisations contribute to networks by providing information or setting regulation or subsidies (local or national governments) or by influencing decision making processes of other organisations in networks (advocacy groups). Throughout the process from natural resource to product or service, industrial networks have important economic, environmental and social impacts on the socio-economic and biophysical systems in which they operate. The sum of complex interactions between organisations affects the rate in which natural resources are used, environmental impacts associated with transformation and transaction of resources and social impacts on local communities, regions or countries as a whole. The aim of this thesis is to understand how industrial networks evolve and how they can be stimulated towards sustainable development.

The first question that has been addressed in this thesis is how to understand the complex interaction between organisational behaviour and industrial network evolution. Organisational behaviour is affected by many functional and implicit characteristics within the environment in which the organisation operates, while simultaneously the environment is a function of non-linear relationships between individual organisational actions and their consequences for both the function and structure of the network. This thesis has identified four different characteristics of industrial networks that affect organisational behaviour:

- Functional characteristics
- Implicit behavioural characteristics
- Implicit relational characteristics
- Implicit network characteristics.

Functional characteristics are those characteristics that are formally recognised by all organisations within an industrial network and which affect their position within the network. Examples of functional characteristics are the price and quantity of resources available, the location and distance of organisations within a network, infrastructure availability or regulation. Implicit characteristics, on the other hand, are those characteristics that impact the decision making process of organisations, but which are not formally part of the network. From an organisational perspective, implicit characteristics are the rules, heuristics, norms and values that an organisation uses to determine its objectives, position and potential actions. Implicit relational characteristics, most importantly trust and loyalty, affect an organisations choice between potential partners and implicit network characteristics are those social norms and values that emerge through social embeddedness. Collectively, these functional and implicit characteristics and their interactions determine the outcome of organisational decisions and therefore the direction of the industrial network evolution.

The complex interaction between these large numbers of characteristics requires quantitative models to explore how different network characteristics and different interactions result in different network evolutions. This thesis has developed an agent-based simulation model to explore industrial network evolutions. To represent the multi-scale complexity of industrial networks, the model consists of four scales. Each scale represents different processes that connect the functional and implicit characteristics of an industrial network to each other. The two basic scales represent the strategic actions

of the organisations on the one hand and the industrial network function and structure on the other. The third scale represents the processes that take place within the mental models of organisations describing how they make sense of their environment and inform their strategic decision making process. The fourth scale represents the social embeddedness of organisations and how social processes create and destroy social institutions. The model has been developed such that it allows for exploring how changes in different network characteristics or processes affect the evolution of the network as a whole.

The second question that has been addressed in this thesis is how to evaluate sustainable development of different evolutionary pathways of industrial networks. First of all, a systems approach has been adopted to explore the consequences of an industrial network to the larger socio-economic and biophysical system in which the network operates. Subsequently, a set of structural indicators has been proposed to evaluate the dynamic performance of industrial networks. These four structural indicators reflect the efficiency, effectiveness, resilience and adaptiveness of industrial networks. Efficiency and effectiveness relate to the operational features by which industrial networks provides a particular contribution to society. Resilience and adaptiveness relate to the system's capacity to maintain or adapt its contribution to society while under stress of temporary shocks or permanent shifts, respectively. Finally, different multi-criteria decision analysis (MCDA) tools have been applied to provide a holistic evaluation of sustainable development of industrial networks.

The third important question that is addressed in this thesis is how to systematically explore the potential evolutionary pathways of an industrial network, which has led to the development of agent-based scenario analysis. Agent-based scenario analysis systematically explores how industrial network evolutions might evolve depending on the perceptions of organisations towards the inherent uncertainty associated with strategic decision making in networks. The agent-based scenario analysis consists of two steps. Firstly, analysts develop a set of coherent context scenarios, which represents their view on the context in which an industrial network will operate within the future. For a bioenergy network, for example, this step results in a set of scenarios that each represent a coherent future of the socio-economic system in which the network might evolve. The second step is the development of a set of 'agent scenarios'. Each agent-

based scenario is based on a different 'mental model' employed by organisations within the network about how to deal with the inherent ambiguity of the future. The organisational perspective towards uncertainty is of major importance for the evolution of industrial networks, because it determines the innovative behaviour of organisations, the structure of the network and the direction in which the network evolves. On the one hand, organisations can ignore future ambiguity and base their actions on the environment that they can observe in their present state. On the other extreme, organisations can adopt a view that the future is inherently uncertain and in which they view social norms and values more important than functional characteristics to make sense of their environment. The mental models are differentiated according to two dimensions: 1) different mental representation of the world and 2) different cognitive processes that can be employed to inform strategic actions. Along these dimensions, different processes can be employed to make sense of the environment and to inform decision making. The thesis has shown that by systematically exploring the different perceptions possible, an adequate understanding of the different evolutionary pathways can be gained to inform the evaluation and development of interventions to stimulate sustainable development.

The final part of this thesis has applied the analysis and methodology developed throughout this thesis to a bioenergy network in the province of Kwazulu-Natal in South Africa. The bioenergy network consists of a set of existing sugar mills with large quantities of bagasse, a biomass waste product, available. Bagasse is currently burned inefficiently to produce steam for the sugar mills, but can potentially be used for the production of green electricity, biodiesel, bioethanol or gelfuel. All of these products have important consequences for the region in terms of associated reductions in CO₂ emissions, electrification of and/or energy provision for rural households and local economic development of the region. This thesis has modelled strategic decisions of the sugar mills, the existing electricity generator, potential independent energy producers, local and national governments and how their actions and interactions can lead to different evolutionary pathways of the bioenergy network. The agent-based scenario analysis has been used to explore how different perceptions of organisations can lead to different network evolutions. Finally, the model has been used to explore the consequences of two categories of interventions on stimulating sustainable development. The conclusions are that both categories of interventions, financial

interventions by national government and the introduction of multi-criteria decision analysis (MCDA) tools to aid strategic decision making, can have both positive and negative effects on the network evolutions, depending on what 'mental models' are employed by organisations. Furthermore, there is no single intervention that outperforms the others in terms of stimulating both functional and structural features of sustainable development. The final conclusion is that instead of focusing on individual or collective targets, emphasis should be placed on the development of interventions that focus on evolutionary aspects of industrial networks rather than functional performance criteria.

This thesis has also highlighted interesting research questions for future investigation. The methodology developed in this thesis is applied to a single case study, but there are still many questions concerning how different industrial networks might benefit from different organisational perceptions towards uncertainty. Furthermore, the role between the mental models and sustainable development requires further investigation, especially in the light of globalisation and the interconnectiveness of industrial networks in different countries and continents. Finally, this methodology has provided a platform for investigating how new technologies might be developed that anticipate needs of future generations. This thesis has provided a first and important step in developing a methodology that addresses the complex issues associated with sustainable development, benefiting both academics and practitioners that aim to stimulate sustainable development.

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Introduction

1.1 Motivation

In our daily lives, especially in the Western world, we are surrounded by numerous products and services that we take for granted. From the first minute we wake up and press the snooze-button on our alarm clock to the last minute when we jump back into bed, every action we undertake involves directly or indirectly some kind of man-made artefact or service. Behind these products and services lies a gigantic web of organisations that provide our daily needs through exchanging and transforming natural resources. Each organisation pursues its own individual objectives, contributing either directly by providing particular resources, technologies or knowledge; or indirectly by setting standards or collecting taxes. Although there is no single organisation that coordinates all these actions, the collective results of all their actions create an industrial networks that grows, adapts and evolves almost autonomously, using more and more resources and providing more and more products and services to new markets and new regions all around the world.

With an exponentially increasing world population and limited natural resources, there is eventually a point in time where changes in our current practices are inevitable in order to sustain the natural biosphere that sustains us. Natural resources will have to be transformed into goods and services more efficiently and effectively, the negative environmental and social impacts of production and transport processes will have to be reduced and our production system will have to become more resilient and adaptive to future shocks and shifts. However, a transition towards an evolutionary pathway that is sustainable is an enormous challenge. Firstly, there is, and will be, no single organisation that would be able to coordinate such a transition. Secondly, it is unclear

how actions of individual organisations contribute to the performance and evolution of industrial networks as a whole. Without any knowledge about the complex interaction between organisational behaviour and industrial network evolution, it is impossible to determine a set of guidelines for strategic behaviour of industrial organisations, governments or advocacy groups that stimulate sustainable development. This thesis explores the relationship between strategic behaviour of individual organisations and their effects on industrial network performance as well as evolution in the context of sustainable development.

1.2 Aim

The aim of this thesis is to develop a methodology that provides insights and understanding about the complex relationship between individual strategic behaviour of organisations on the one hand, and industrial network performance and evolution on the other hand. In particular, this thesis will focus on how changes in strategic decision making processes of organisations can contribute to sustainable development of industrial networks. The methodology will be developed on the basis of a case study of a bioenergy network in an emerging economy. The inherent complexity of this case study affords ample opportunity to explore the viability and usefulness of the proposed methodology. The challenge of understanding the relationship between strategic behaviour and industrial network evolutions in the context of sustainability is particularly topical and relevant to bioenergy networks. Bioenergy networks have the potential to contribute to the provision of goods and services on the basis of renewable resources; however it is unclear which infrastructures, technologies and network configurations contribute most to current and future needs in terms of sustainability (UN-Energy 2007). Firstly, there are challenges in terms of the contribution that bioenergy networks can make to sustainability. Appropriate trade-offs between local impacts on rural development and the global environment are required. Secondly, there is large uncertainty around the effects of the different value chains which intersect around this problem, from small-scale local production of biofuels to large-scale production of electricity. Finally, there are questions surrounding the future of bioenergy networks and the appropriateness of the different pathways in the light of future uncertainty.

1.3 Research question

The relationship between organisational behaviour and industrial network evolution is complex. The properties and patterns of an industrial network level are a function of the relationships and interaction between its interdependent organisations, their perspectives and responses to each other, as well as the complex interaction between the system level properties and the organisations individual objectives (Bar-Yam 2003: 2). The driving force for the evolution of the network is strategic decisions by organisations autonomously pursuing their individual objectives within a constantly changing external environment. However, the consequences of their decisions for the network evolution are not linear and straight forward, but depend on the responses of other organisations in the network, and on unknown externalities that impact the network as a whole. Each and every one of these strategic decisions does not only change the course of the individual organisation within the network, but also affect the evolution of the industrial network as a whole. Figure 1-1 schematically represents the interaction between organisational behaviour and industrial network evolution.

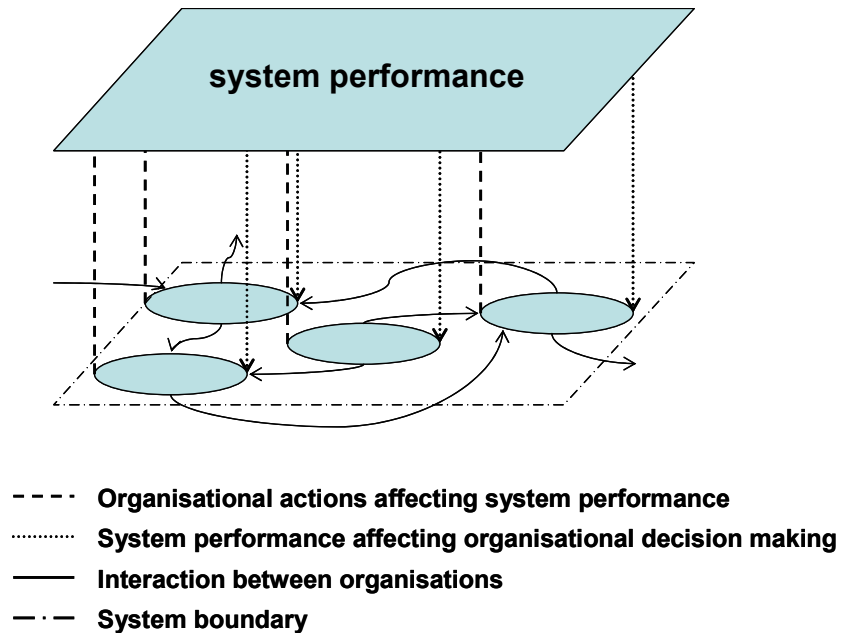


Figure 1- 1 From organisational behaviour to industrial network evolution

Given the complex relationship between organisational behaviour and the evolution of industrial networks, the central question of this thesis is:

How does organisational behaviour affect industrial network evolution and which interventions can stimulate sustainable development of industrial networks?

This thesis is developed on the basis of a variety of research areas that have been focusing on particular elements of this research question. The complex interaction between adaptive organisations and system evolution has been studied as Complex Adaptive Systems (CAS) (Holland 1995). Strategic behaviour of organisations within industrial networks have been studied in psychological (Simon 1956; Weick 1995), sociological (Granovetter 1973; DiMaggio and Powell 1983; Giddens 1984; Luhmann 1984), economic and organisational sciences (Cyert and March 1963; Ansoff 1965; Ackoff 1974; Mintzberg, Raisinghani et al. 1976; Porter 1980; March 1988). Furthermore, a variety of research areas have been developing indicators to evaluate the sustainable development of systems (Ayres 1993; Kaufmann and Cleveland 1995; Jackson 1996; Hawken, Lovins et al. 1997; Wackernagel, Onisto et al. 1999; Robert 2000; Folke, Carpenter et al. 2002; Ehrenfeld 2004). However, the unique contribution of this thesis is to combine these insights into a common framework of analysis using a systems engineering approach. From this perspective, the thesis question can be divided into five sub questions:

1. What are the major determinants of organisational behaviour in industrial networks?
2. How does organisational behaviour affect the performance and evolution of industrial networks?
3. How can sustainable development of industrial networks be evaluated?
4. How can the effect of interventions in industrial networks to stimulate sustainable development be analysed?
5. Which methods are available to analyse sub questions 1-3?

The first four questions will be addressed in chapter 2, 3, 4 and 5 respectively, with each chapter addressing the methodological challenges associated with these questions. Section 1.4 will discuss, in some more detail, relevant research areas that have been focusing on some of the issues related to these research questions, and how these research questions fit in with the existing work and understanding of the relationship between organisational behaviour and sustainable development.

1.4 Conceptual foundations

The relationship between organisational behaviour and industrial network evolution is complex. Several sciences have studied and focused on some, or more, aspects of the complex interaction between organisational behaviour and industrial network evolution. Their concepts and insights provide a rich background for the analysis of the complexity between organisational behaviour and industrial network evolution in the context of sustainability.

In this thesis, the definition of multi-scale complexity by Bar-Yam (2004) is adopted. According to his definition of complexity, the total complexity of a system is a function of the degrees of freedom and interdependencies at different scales of observation (Bar-Yam 2004). A more detailed discussion on complexity is provided in box 1.1. Throughout this thesis, boxes provide ancillary information on issues related to this thesis. The text in the boxes is aimed at the interested reader and does not form an integral part of the main text.

Box 1.1 What is complexity?

The question of complexity has been addressed by a large number of scholars in a number of different research fields, and several quantitative measures have been proposed to quantify complexity. The most well known indicator for complexity is the Algorithmic Information Content (AIC), which measures complexity by the length of the shortest description required to describe a system. However, a critique on this approach is that it fails to recognise that the description of a system does not necessarily address the inherent logic behind a system (Strogatz 2001:48). For example, Shakespeare's works are vastly complex, however they can be described in a shorter description than a text of gibberish of the same length (Gell-Mann 1995:2).

Gell-Mann (1994) developed a methodology to describe complexity of a system on the basis of the number of 'regularities' or rules observed in the system. A definition on the basis of regularities is different from descriptive complexities, because it determines the system complexity by its 'emergent' properties rather than by its state. For example, Shakespeare's work is more complex than gibberish, because it results from applying a set of distinct regularities or rules (while gibberish has no regularities).

A critique on Gell-Mann's approach is that regularities are observer dependent. A system observed over a short time period and on a coarse scale might reflect less regularities than a system observed over a longer period of time (Bar-Yam 2004:4). To accommodate for the scale dependency, Bar-Yam (2004) developed an indicator to represent the complexity of a system on the basis of multiple scales (see figure 1-2).

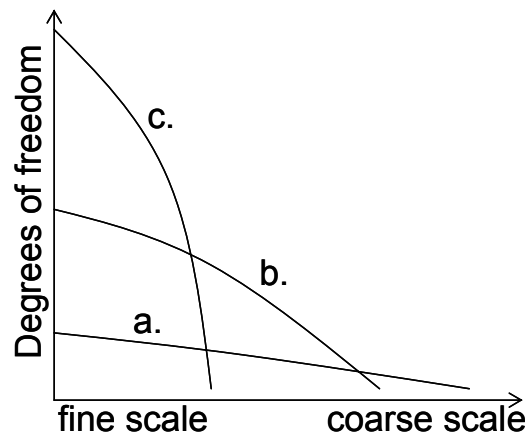


Figure 1- 2 Multi-scale complexity (Bar-Yam 2004:10)

The y-axis shows the degrees of freedom of a system and the x-axis shows the scale of observation from a fine scale to a coarse scale. Lines a, b and c represent the complexity of three systems over multiple scales of observations.

Box 1.1. What is complexity (continued)

According to the definition of multi-scale complexity, the total complexity of a system is a function of the degrees of freedom at different scales of observation. A completely random system has a high degree of freedom on a microscopic scale, but does not exhibit any emergent properties (ie regularities) on a macroscopic scale (system C in figure 1-2). When the degrees of freedom of a system are coherent on both a fine and a coarse scale, the system has a low value of complexity over a large range of scales (system A). Finally, complex non-equilibrium systems have fewer degrees of freedom on a microscopic level than completely random systems, but may have the ability to display emergent behaviour on a macroscopic scale (system B) and can therefore be more complex.

This thesis uses the concept of multi-scale complexity as a conceptual framework to analyse industrial networks. It will examine how the degrees of freedom of individual organisations affect their behaviour and therefore regularities on a macroscopic scale, characterised by different network evolutions. Simultaneously, it will examine how different network evolutions affect organisational behaviour by restricting organisational actions through “lock-in” effects of technological and infrastructural investments, or by opening up new opportunities for organisations to innovate.

The next sections provide the framing of these research questions into a broader research context. Firstly, section 1.4.1 will discuss the concept of an industrial network. In particular, it is argued that the theory of complex adaptive systems (CAS) can be applied to industrial networks. Section 1.4.2 discusses how industrial networks have been conceptualised and studied in the past. It concludes that in order to study the evolution of industrial networks, both strategic behaviour of industrial and non-industrial organisations have to be analysed within a common framework. Section 1.4.3 will place the research questions on organisational behaviour within the context of existing research on organisational decision making. Three elements of this research will be highlighted:

- 1) What is currently known about how organisations make strategic decisions?
- 2) What role does uncertainty play within decision making processes and how is this currently formalised?
- 3) What is known about the role of technology and innovation within industrial network evolutions?

Section 1.4.4 discusses existing frameworks for analysis of sustainable development and the extent to which they are applicable to assess and evaluate the evolution of industrial networks. It argues that sustainable development of industrial networks requires an assessment of both their function and structure simultaneously.

1.4.1 Complex Adaptive systems

It is argued in this thesis that industrial networks can be characterised as CAS. The term 'complex adaptive systems' originates from research at the Santa Fe institute, where they defined CAS as a dynamic network of agents that constantly act and respond to each other. The overall evolution of the network is the result of agent decisions and the interaction between the agent and the network (Holland 1995:15).

Complex adaptive systems display four properties: emergence, co-evolution, self-organisation and adaptiveness. The concept of emergence is the idea that system patterns are a function of interdependencies between subsystems. As a result of these interdependencies, there is no single description that can explain the system properties on the basis of the properties of the subsystem (Humphreys 1997:16). In other words, in a CAS properties on a system level (i.e. a particular economic performance of an industrial network) can be obtained through different configurations of the system components (i.e. different organisational networks could lead to the same economic performance). CAS are therefore always multi-scalar (Bar-Yam 2004; Abbott 2007:11). The interdependencies between subsystems can be described by a set of rules that govern the interaction between subsystems. These rules can be strictly formal and conform to a precise logic, but they can also involve randomness and/or change over time. The configuration of the components at any specific moment constitutes a 'state' of the system. A specific state will activate the applicable rules which then transform the system from one state to another (Cilliers 1998:14).

Co-evolution refers to an evolutionary change in a trait of a system component in response to a trait of another subsystem, which is then followed by an evolutionary response by a second subsystem to change in the first (Robertson 2004:72). Co-evolution not only takes place between components within the system, but also between the components and the system, and between the system as a whole and other systems. In formalising CAS into models, this latter form of co-evolution is captured as

an external effect on the highest level of the system and as such affects the system's performance (Newton 2002; Robertson 2004).

The concept of 'self-organised criticality' or self-organisation refers to the metaphor of the system being "on the edge of chaos". It is the growing awareness emerging from the study of CAS that order arises out of disequilibrium, and that assumptions about equilibria are actually unusual within CAS (Daneke 2001:524). The reason for this phenomenon is that CAS have to be able to adapt their structure in order to cope with changes in the environment. As long as this structure is able to cope with changing external forces, it will stay in a quasi-equilibrium, but as soon as a certain threshold has passed the structure rearranges itself (Cilliers 1998:12). It is important to understand that self-organisation is as much a product of systemic forces as a result of individual (non-) rationality (March 1988 in Daneke 2001:519).

CAS can be distinguished from complex systems by agency in their system components; the ability of the system components to intervene meaningfully in the course of events in the system (Giddens 1984). The concept of adaptiveness is a result of this agency and, according to Axelrod and Cohen (1996), is the outcome of a selection process that leads to an improvement according to some measure of success. This measure of success can be related to the individual success of the agent. However, success can also be related to success from a systems perspective rather than an individual perspective. The theory of 'the selfish gene' refers to the adaptiveness of individuals on the basis of system success, when it discusses that the driving force for evolution is not the survival of the individual, but the survival of the species.

These four complex adaptive system characteristics, emergence, co-evolution, self-organisation and adaptiveness are also present in industrial networks (Kempener, Cohen et al. 2008). The adaptive features of organisations result in a co-evolution between organisations and industrial network structures. The social embeddedness of organisations is in essence self-organisation, which through social institutions of norms and values provides stability and social cohesion in the network. Finally, the interaction between adaptiveness, co-evolution and self-organisation create the emergent system properties of industrial networks.

The characterisation of industrial networks as complex adaptive systems brings up particular questions on the interrelationships between organisations in industrial networks? How does the interrelationship between organisations result in network structures? How do network structures inform self-organisation? How does the co-evolution between different organisations and the network as a whole inform adaptive behaviour of organisations? How does the adaptive behaviour of organisations lead to particular network evolutions? These questions will be addressed in more detail in chapter 2 and 3.

The next section will discuss in more detail some of the research areas that have focused on some of the aspects of industrial network evolution within the context of sustainable development. The aim of this discussion is to highlight key questions that form the basis for this thesis.

1.4.2 Conceptualisation of industrial networks

Industrial networks have been studied in a variety of research fields and different conceptualisations of industrial networks exist. Economic and administrative sciences have conceptualised industrial networks as markets of buyers and suppliers (Jovanovic 1982; Klepper and Graddy 1990), operational research use concept of supply chains and more recently supply networks (Akkermans 2001; Choi, Dooley et al. 2001; Thadakamalla, Raghavan et al. 2004), while other research fields like industrial ecology or innovation studies have looked at industrial networks as regional clusters of interconnected organisations exchanging resources, information and knowledge (Ehrenfeld and Gertler 1997; Porter 2000; Asheim, Coenen et al. 2006). Finally, social sciences have conceptualised industrial networks as a group of interconnected stakeholders consisting of all persons or groups with legitimate interests in the function of (a group of) industrial organisations (Donaldson and Preston 1995; Shankman 1999).

Despite the different conceptualisations and research focus, there are some similarities between the different research fields. Industrial networks are networks of organisations that exchange resources with each other (Podolny 2001:33). Organisations can be industrial, governmental and non-governmental organisations or represent advocacy groups or households. Resources can be “anything which could be thought of as a strength or weakness of a given organisation” (Wernerfelt 1984:172). They are semi-

permanently tied to the organisation and can exist of personnel or capital, but can also include brand names, in-house knowledge, regulation or organisational strategies.

Resources determine both function and structure of networks. Firstly, the specific function of each organisation is determined by resources availability as well as the unique set of resources an organisation controls (Barney 1991:102). Secondly, resource allocation decisions determine which resources flow in and out of the organisation, and dictate the number and type of relationships to other organisations (Hakansson 1987). The relationships can be seen as 'pipes' form one organisation to another through which resources flow forming the structure of an industrial network (Podolny 2001:33).

Finally, both function and structure are dynamic quantities, influenced by competition between organisations trying to maintain or improve their position within the network (Jacobson 1992:786). These dynamics imply that industrial networks are inherently associated with uncertainty. The first type of uncertainty is egocentric and involves uncertainty about the potential consequences of particular strategic decision. The second type of uncertainty is about other organisations and the resources they provide or demand (Podolny 2001:37). Both uncertainties can be independent and determine, for an important part, the operation and evolution of industrial networks¹. Through time, different operational paradigms have attempted to address market uncertainty through either vertical integration, outsource or different licencing-subcontracting models (Ackoff 1974:12; Porter 1996:70). However, regardless which operational paradigm is used, uncertainty is a fundamental part of industrial networks and needs to be understood to analyse the function, structure and dynamics of industrial networks through time (see chapter 5).

Considered from an organisational perspective, the function of an industrial network is to facilitate the exchange of resources, thereby sustaining each organisation's position within the network. However, from a macro-spatial perspective, the function of industrial networks is defined in terms of more global attributes, such as the overall welfare they

¹ Podolny (2001) provides an example of four different industrial networks with each different characteristics: vaccines, wheat, high-yield debt banking and roof tiles. For example, vaccines are developed in an industrial network where egocentric uncertainty is high, but altercentric uncertainty is low. In contrary, the roofing industry operates completely different than vaccines, because it has low egocentric uncertainty and high altercentric uncertainties. High-yield debts have high uncertainty in both dimensions, while the wheat industry has low uncertainty in both dimensions. (p. 39).

provide to society. This type of functionality can be measured in economic terms of Gross Domestic Product (GDP) contribution or employment creation, or in terms of the final products and services provided to households or other industrial networks. Although resource transformations and exchanges are also the basis for the industrial network functionality as a whole, the behaviour of specific organisations within a network, and the way in which they exchange resources, are of less concern from this perspective.

In this thesis, both an organisational and a macro-spatial perspective is required. The individual organisations, and the processes by which they choose to position themselves within the network, are important determinants for the structure and evolution of industrial networks. The macro-spatial functionality of industrial networks is important to determine and assess sustainable development of industrial networks in terms of their contribution to the socio-economic and biophysical system in which they operate. Therefore, this thesis defines industrial networks as ***any network of organisations that directly or indirectly contributes to the provision of a particular functionality to society through the transaction and transformation of resources***. Organisations with a direct contribution are those organisations that contribute to the product or service itself through resource exchange and transformation, while organisations that indirectly contribute are those that affect the decision making process of organisations that transform or exchange resources.

1.4.3 Organisational behaviour in industrial networks

Organisational behaviour is the driving force for network evolution. Every decision taken affects other organisations within the industrial network, which subsequently have to reposition themselves within the changed environment. This perpetual interaction between organisational behaviour and industrial network characteristics is at the core of complexity of industrial networks.

Within this context, it is the strategic decisions of organisations that have the most impact on network evolution, especially in the long run. Strategic decision making determines the success of organisations (Markides 1999: 6). In general terms, strategic decision making is defined as a 'set of consistent behaviours' concerned with the match between the internal capabilities of the organisation and its external environment determining the course of the organisation through time (Ansoff 1965:5; Mintzberg,

Raisinghani et al. 1976:246; Mintzberg 1978:941; Eisenhardt and Zbaracki 1992:17; Itami and Numagami 1992:119; Kay 1999:2). Any strategic decision changes the way in which an organisation exchanges and/or transforms resources, which subsequently changes the industrial network characteristics. Simultaneously, changes in industrial network characteristics inform the strategic decision making processes of other organisations within the network. The process of how an organisation perceives its position within the industrial network and how an organisation decides to change its own performance to match its environment is core to the research question in this thesis. It is the strategic decision making process that drives industrial network evolution and therefore drives its potential contribution to sustainable development.

However, as previously mentioned, it is unknown to any organisation what the potential outcomes of its decisions are going to be. Keynes (1938) described the process by which organisations make strategic decisions as follows: “Most probably, of our decisions to do something positive, the full consequences of which will be drawn out over many days to come, can only be taken as the result of animal spirit – a spontaneous urge to action rather than inaction, and not as the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities.” (Keynes 1938:161-162). It raises an issue of rational versus irrational behaviour in organisations, a discussion which is still unresolved (Jungermann 2000). It has become clear that rational behaviour defined as a ‘powerful analytical and data-processing apparatus’ (Williamson 1981:553) does not exist, because information about the consequences is unknown, computational capabilities are bound and preferences are not stable (Simon 1957:241). Further research has shown that there are many other processes that impact on strategic decision making: humans and organisations are biased towards risk (Tversky and Kahneman 1981), routines rather than maximising behaviour inform decisions (Nelson and Winter 1982) and social institutions informs decision making (DiMaggio and Powell 1983). However, the argument that all behaviour is irrational has also been dismissed, because some argue that these alternative decision making processes, ie the use of routines, heuristics and norms and value to inform decisions, are a rational way of making decisions in an uncertain environment (Williamson 1981:555). Furthermore, it is argued that strategic decisions may appear biased if analysed statically, while they might be very logical and functional when considered in a continuous and changing environment (Jungermann 2000:582).

Industrial networks have increasingly become more complex and, as a consequence, the uncertainty that organisations face has increased. Firstly, industrial networks have shifted from primarily local networks to global networks in which resources come from all over the world (Castells 2000). Secondly, products and services themselves become increasingly complex requiring a large number of resources combined in order to provide their improved functionalities. Finally, the capital markets that govern the production of products and services in many developed countries favour competition between organisations, products and services. Competition requires organisations and industrial networks to continuously improve, either in cost or functionality, and innovate their products and services to maintain competitive advantage. The increased demand for improvement and innovation has increased the development of products and services making networks more dynamic and unpredictable².

It is increased complexity of industrial networks and strategic interactions, that makes it essential to adopt simplifying strategies to guide decision making (Levy 1994:172). Forrester (1961) and Sterman (2000) refer to these simplifications as mental models, which includes beliefs about the parameters, variables and relationships that describe how the system operates, along with the system boundaries and time horizons considered (Forrester 1961:49; Sterman 2000:16). Depending on the level of uncertainty, different organisations can apply different mental models to abstract the required information and convert that information into a particular action. In this thesis, it is argued that an understanding of the dynamic impacts of different mental models on industrial network evolution is central to the development of interventions that can stimulate sustainable development. A methodology to explore different mental models will be discussed in more detail in chapter 5, in particular section 5.4.

In the context of this discussion, economics, sociology, psychology and organisational sciences have developed numerous theories that attempt to capture and describe processes and variables that play a role in organisational behaviour on a strategic level. Each theory represents a different 'mental model', ranging from neoclassical economics viewing organisations as rational entities that choose those options which maximise their

² For example, the number of granted patents has increased 80% between 1990 and 2004 (www.wipo.org, accessed May 2006).

internal utility, to theories of social constructivism, which suggests that organisations use legislative, normative and cognitive norms and values to inform their behaviour. These theories have often contradictory views of what industrial network characteristics and processes govern organisational behaviour and therefore provide different views on how industrial networks evolve over time. To explore the effects of different mental models, a coherent framework is required allowing analysis of different organisational behaviours and the industrial network characteristics that inform their decision processes. Such an analytical framework is presented in chapter 2.

In the light of this discussion, the following research questions are formulated:

- ***How are organisational behaviour and industrial network characteristics interrelated?***
- ***How does the interrelationship between industrial networks characteristics and organisational behaviour affect the system performance and network evolution?***
- ***Which modelling tools are available to analyse these effects?***

Chapter 2 develops an analytical framework that places different theories on organisational behaviour in the context of industrial network characteristics. The interaction between organisational behaviour and industrial network evolution as well as how this interaction can be analysed is discussed in chapter 3. A framework to evaluate the dynamic functional and structural of industrial networks is discussed in chapter 4 and a methodology to analyse the impacts of different 'mental models' of decision making on industrial network evolutions is discussed in chapter 5.

1.4.3.1 Innovation

Innovation is the successful diffusion of an economic and socially accepted invention (Perez 2004:220). As such, innovation can be seen as the outcome of a decision making process whereby individual organisations choose to adopt a new technology over an existing one. This decision to adopt, like any other strategic decision," involves uncertainty in an essential way"(Nelson and Winter 1977:47). According to Rogers, "the perceived newness of an innovation, and the uncertainty associated with this newness, is a distinctive aspect of innovation decision making, compared to other types of decision

making” (Rogers 1995:161). The uncertainty associated with innovation can be categorised into ‘technology-centred’ uncertainty and ‘system structure-centred’ or ‘market’ uncertainty (Freeman and Soete 1997:245). Firstly, there is technical uncertainty about the consequences of new technology and whether it can deliver what specifications promise (Freeman and Soete 1997:244). Secondly, there is system structure-centred uncertainty about wider diffusion of a particular technology of choice, whether other technologies might become superior and whether future infrastructural developments will support the technology of choice. The adoption process of new technologies is thus not only affected by individual preferences, but also by strategic behaviour of other organisations in the network (Bass 1969; Abrahamson and Rosenkopf 1993; Abrahamson and Rosenkopf 1997). The role of innovation in industrial networks is directly linked to uncertainty and organisational behaviour and is an important issue to explore in the context of sustainable development.

In principle, there are two kinds of innovative technologies: radical and incremental innovations³. Incremental innovation are successful improvements of existing products and processes and are closely aligned with the process of ‘learning by doing’ or ‘learning by experience’ (Berglund and Soderholm 2006; Pan and Kohler 2007). On the other hand, radical innovations are truly new products and processes that break with existing paradigms, are built on new principles and open up new technological and economic opportunities (Kemp 1994:1034; Ehrenfeld 2004:5). Radical innovations are often a result of ‘learning by experiment’ either in individual organisations or in strategically placed niches, where a number of organisations work on the development of new innovations (Raven 2005).

There is a tension between incremental innovation on the one hand, and radical innovation on the other (Arthur 1989; David and Rothwell 1996; Axelrod 1999), especially in the context of sustainable development in industrial networks. Does continuous incremental innovation provide evolutionary pathways that are sustainable, or does incremental innovation inhibit the possibility of radical new innovation to enter the market and provide step changes towards an improved sustainable development? This tension is of particular interest to sustainable development in industrial networks,

³ Others have introduced also architectural and modular innovations as two subclasses of innovation between radical innovation on the one hand and incremental innovation on the other hand.

where technology is often seen as a means to reduce the environmental burden of increased production (Hart 1997:71). Furthermore, a transition towards a more sustainable future is often related to the introduction of radical innovations, which can provide new techno-economic paradigms for future developments towards sustainability (Freeman 1994; Kemp 1994; Rotmans, Kemp et al. 2000; Geels 2002; Ehrenfeld 2004).

To understand the role of innovation in industrial network evolution, it is important that the innovation diffusion process is seen in relation to strategic decision making processes within organisations and how the different 'mental models' impact on the different types of innovation and the diffusion of innovation. In chapter 5, the role of different mental models on the evolution of industrial networks will be coupled to an exploration of how these different mental models impact on innovation decisions. In particular, the following questions will be addressed:

- ***What is the relationship between strategic decision making, innovation and system uncertainty in the evolution of industrial networks?***
- ***How do different kinds of uncertainty affect a potential transition to a more sustainable industrial network?***

1.4.4 Sustainable development of industrial networks

The previous paragraphs have argued that industrial networks are complex adaptive systems, which consist of a number of organisations that, through resource transformation and exchange, provide a particular functionality towards the socio-economic and biophysical system in which they operate. This definition of an industrial network has certain implications for assessing the sustainable development of an industrial network. Firstly, it requires a distinction between sustainable development and sustainability. Sustainable development is the process by which an industrial network moves towards sustainability⁴. Secondly, it should be recognised that there are different evolutionary pathways by which an industrial network can move towards sustainability. The sustainable development of any of these pathways requires a methodology that not only assesses the function of industrial networks, but also takes into consideration the structure and dynamics of industrial network evolution and the non-linear relationship

⁴ Chapter 4 discusses in more detail what the concept of sustainability might entail, which is not necessarily a fixed state or end point.

between organisational behaviour on the one hand and system performance on the other⁵.

The functionality of industrial networks and its implications for sustainable development have been discussed, amongst others, by Jackson (1996). He places sustainable development of industrial networks within the context of the larger socio-economic and biophysical system in which they operate, interacting through resource exchange. Firstly, sustainable development of industrial networks can be assessed by the needs that they provide to society. This is reflected in the contribution of an industrial network towards its socio-economic system. Secondly, sustainable development of industrial networks can be assessed according to the quantity of natural resources that are used to provide amenities and in how far the industrial network provides a structure that allows the use of high quality resources in the future (p. 13). These principles are derived from the first and second law of thermodynamics and reflect the effects of industrial networks on the biophysical system (Jackson 1996).

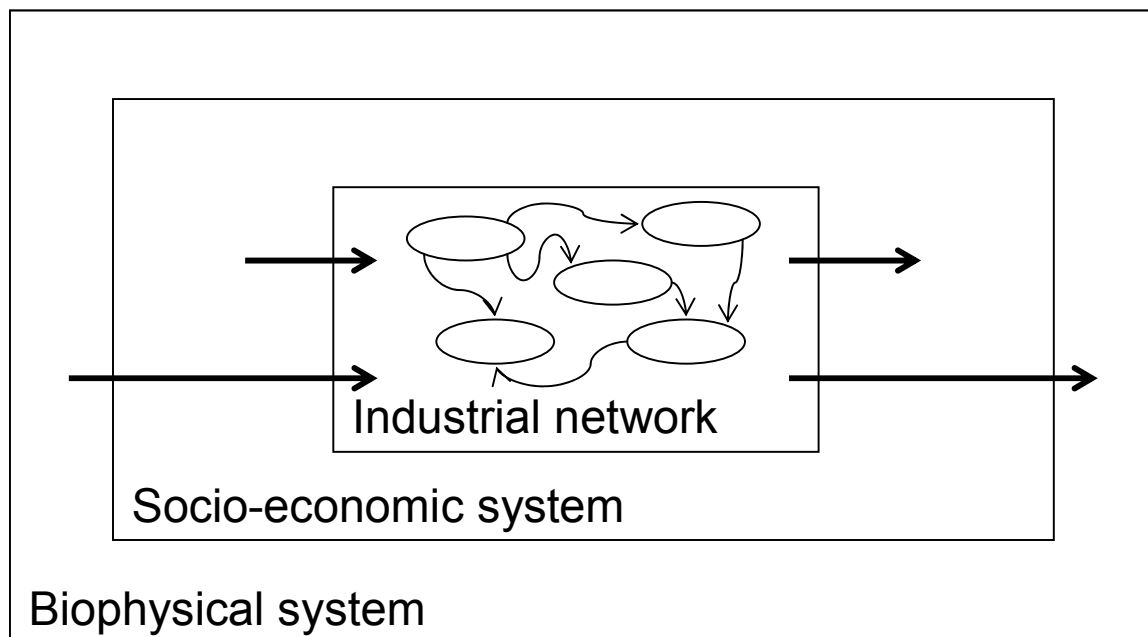


Figure 1- 3 Industrial networks operating within a socio-economic and biophysical system

⁵ Walner (1999) defines networks according to seven dimensions: objective, actors involved, exchange variables, intensity of the connection, temporal developments, structure and organisation and spatial area of effect. All these dimensions fall within dimensions identified in this thesis.

There are several methodologies that have been developed to assess sustainable development of industrial networks in the context of the wider systems in which they operate. A life-cycle approach can be used to measure the functionality over the total system. Nowadays it is generally acknowledged that functionality of industrial networks should not only be measured in terms of the economic benefits that it provides to the region or country in which it operates, but that its functionality should also be measured on the basis of social and environmental contributions. The system boundary over which the life-cycle analysis takes place includes all organisations within an industrial network that in one way or another contribute to the transformation of resources entering the network and goods and services leaving the network. Thus, this includes economic, social and environmental impacts of intermediate organisations, such as transport companies, effects of infrastructure development or economic, social and environmental effects of advocacy groups and/or communities. Other methodologies, like eco-efficiency and industrial ecology, have not only focused on the function of a system in terms of economic, social and environmental impacts as outputs, but also focused on processes by which inputs are converted into outputs. From this perspective, those systems that are more efficient or effective in providing a particular functionality are preferred over those systems that require more inputs or higher-grade inputs to achieve the same functionality. In this thesis, efficiency is defined by the degree of waste produced by an industrial network transforming natural resources into goods and services. Effectiveness is defined by the degree by which an industrial network provides high value goods and services considering the value of resources entering the network.

However, the assessment of industrial network function is only one part of sustainable development. Structural features of industrial networks can be as important as functional characteristics, particularly in cases where industrial networks are threatened by external forces impacting on the system. The structure of the industrial network is not only determined by which organisations are directly or indirectly connected, but also by feedback loops that exist between different organisations, their actions and potential responses of others as well as information and options that are available to individual organisations.

Biological studies have developed a set of criteria to evaluate system structures, such as resilience, robustness and adaptiveness. However these concepts have only been

applied recently to industrial networks (Folke, Carpenter et al. 2002; Allenby and Fink 2005; Fiksel 2006). Furthermore, explicit consideration of both function and structure simultaneously is, as far as aware, limited only to a very small number of recent publications (see for example Sartorius 2006; Hooker 2007; Voinov and Farley 2007).

The third challenge for sustainable development is engagement with dynamic features of industrial networks. These dynamics imply that any attempt to create a new sustainable order will be interwoven with actions of other organisations in the network. An organisation introducing a first step towards such an order will therefore find difficulties to predict what the consequences of sustainable actions will be for the network as a whole (Newton 2002:524). Transition management has been developed as one way of dealing with the challenge of paradigm shifts towards more sustainable systems (Rotmans, Kemp et al. 2000). Transition management involves 'system innovations', which describe a process of technological and social processes resulting in system transition (Kemp and Loorbach 2003:4). Although there has been much research on understanding the building blocks (parameters, variables and processes) that drive system innovations (see Geels 2002 for a critical overview), it is difficult to translate this understanding into practical guidelines for organisations operating in such networks. According to Newton, the dynamic features of industrial networks and the implications for sustainable development in organisational decision making have not sufficiently been addressed within current organisational literature (p. 529).

Finally, there is the difficulty of complexity in industrial networks. Improved organisational sustainability does not necessarily mean that the overall industrial network in which organisations operate performs any better in terms of sustainability. Sustainability, especially if assessed from a systemic perspective and seen as a particular end goal, involves political, environmental and social issues that extend beyond the mandate and the capabilities of any single organisation (Shrivastava 1995:936). To achieve sustainability on a systems level requires both cooperation and interaction between organisations (Ackoff and Gharajedaghi 1996:2; Axelrod 1999:3). Although there are several frameworks developed that provide sustainability indicators for organisational decision making, the systemic processes are neglected in the literature on sustainability indicators for decision making (Daneke 2001:514). Kempener (2003), for example, shows that in the chemical industry improved energy efficiency can be achieved over the

total supply chain from cradle to grave if some organisations increase their energy use so that others can reduce their energy consumption more drastically. This example is one of many that can be thought of whereby use of sustainability indicators on an organisational level impedes sustainable development of the system as a whole.

Although the three network characteristics of function, structure and dynamic interaction have been discussed separately above, they all play a role simultaneously in the sustainable development of industrial networks. The question remains how these three industrial network characteristics affect the performance, evolution and contribution of the network towards sustainable development. In this thesis, it is argued that structure can only be evaluated in the context of a particular function, and that sustainable development of an industrial network should be assessed dynamically. In other words, ***different functional features of industrial networks, ie their economic, environmental and social impacts, should be related to the structure of the system in terms of its efficiency, effectiveness, resilience and adaptiveness at any point in time.*** This analysis will be discussed in more detail in chapter 4, where the following research questions will be addressed:

- ***What is the relationship between industrial network function, structure , governance and context in terms of sustainable development of industrial networks?***
- ***How can different industrial network features be evaluated in the context of sustainable development?***
 - ***Which modelling tools are available to analyse these effects?***

The relationship between industrial network characteristics and sustainability will be analysed in chapter 4, while the interrelationship between network structures and organisational behaviour will be discussed in chapter 2. Modelling tools and their applicability will be discussed in chapter 3.

1.4.5 Interventions to stimulate sustainable development

The final aim of this thesis is to develop a methodology to develop and assess interventions that can stimulate sustainable development of industrial networks. Interventions can be thought of as deliberate introduction of policy instruments, like

subsidies, regulation or information dissemination; however they can also consist of a shift in how organisations make strategic decisions. The question that will be addressed is how interventions affect strategic behaviour of organisations and therefore industrial network evolution as a whole. A methodology is required to assess which interventions stimulate sustainable development of industrial networks and how robust these interventions are if organisations respond differently. From this perspective, both systems engineering and complex systems theory can provide insights. Systems engineering has dealt with management, control and design of complex systems, while complex systems theory has merely analysed what processes and mechanisms determine and drive complexity (Abbott 2007:11). By combining both insights, it is possible to use powerful tools of modelling and simulation from systems engineering with insights of multi-scale complexity of complex systems theory. Multi-scale complexity, as argued in section 1.4.1, is the result of emergence, system properties that are a function of interdependencies between subsystems.

In chapter 3, it is argued that by developing multi-scale models of organisational behaviour in industrial networks, it is possible to simulate the complex interaction between organisational behaviour and industrial network characteristics. These simulation models are referred to as “agent-based”, because agent-based models (ABM) model the system from the perspective of the individual decision maker within its operating environment (Epstein 1999; Axtell 2000; Tesfatsion 2001; Bonabeau 2002; Bousquet and Le Page 2004). Furthermore, ABM explicitly consider the mental models that organisations use, because each agent in an ABM does not have perfect knowledge about other agents in the system and how the system will evolve over time (Edmonds 1998:304; Pahl-Wostl and Ebenhoh 2004:2; Janssen 2005:5). It is argued within this thesis that ABM should be augmented with system dynamics models, which are able to describe the institutional processes that take place in industrial networks and which cannot be attributed to individual organisations. Subsequently, these models can be used to explore how different interventions affect the evolution of the system as a whole.

The development of a simulation model to explore the role of organisational behaviour in industrial network evolution will be explored in chapter 3, while chapter 7 will illustrate how the impact of interventions on sustainable development of a bioenergy network can be explored. In particular, this thesis will address the following questions:

- ***Which interventions can be developed that stimulate sustainable development of industrial networks?***
- ***Which assessment tools are available to analyse the effectiveness of interventions to achieve improved sustainable development?***

These questions will be addressed in more detail in chapter 5 and illustrated in chapter 7.

1.4.6 The role of bioenergy in sustainable development

A bioenergy network in an emerging economy is used to illustrate that the methodology developed within this thesis can be used to explore and develop interventions to stimulate sustainable development of such networks. Bioenergy networks have recently received much attention (BRAC 2006; DOE 2006; Caesar, Riese et al. 2007; Clift 2007; Elghali, Clift et al. 2007; Kintisch 2007), because bioenergy is perceived as 'carbon neutral' and it can contribute to the reduction of CO₂ emissions by replacing fossil fuels in both electricity production and oils. However, bioenergy has also received much critique. Firstly, the enormous increase of ethanol and biodiesel production on the basis of maize and wheat in Europe and the US has driven up the prices for food, and many families are affected by the increased food prices. Furthermore, the EU targets on biofuels have spurred the large-scale production of palm oil and soy bean oil in South-East Asia and South America, whereby large areas of rainforest are burned down and replaced by biofuel crops. Finally, the transport and processing of biomass into electricity or biofuels requires energy, which for some biomass sources drastically reduces the netto reduction of CO₂ emissions that the biomass provides.

The bioenergy network that is explored in this thesis is located in the region of Kwazulu-Natal in South Africa and is based on use of bagasse as a energy source. Bagasse is a waste product of the sugar industry and is therefore not associated with any negative impacts on food production or use of agricultural land. The production of sugar in KwaZulu-Natal has a long history with the first plant being built in 1852 (Lewis 1990:70). Currently, there are 12 sugar mills each producing between 235 and 683 Ktonnes of bagasse, which is currently burned inefficiently to produce steam requirements within

each sugar mill⁶. However, bagasse could potentially be used to generate an estimated 3031 GWh per year, which exceeds the industries' own energy needs of 700 GWh p.a. (DME 2004:5). The development of a bioenergy network has not only the potential to contribute to reduction of CO₂ emissions in South Africa, but it can also have important economic and social implications. There are currently high unemployment rates in KwaZulu-Natal and with decreasing sugar prices there is a need for development of new industries. The production of bioenergy on the basis of bagasse could attract new businesses as well as local employment through development of localised bioenergy networks. Furthermore, with increasing demand of electricity, development of large-scale electricity production could contribute to reduce the expected shortage in electricity generation capacity in the near future. Recent electricity blackouts (2007-2008) in the country due to failures within the national grid have once again focused attention on the potential for independent power production. The sugar mills are keen to be at the forefront of this initiative. There are also social benefits from development of a bioenergy network. Currently, around 50% of households in Kwazulu Natal are not electrified and large-scale electrification programmes have failed to connect all households and schools to the main electricity grid. Through development of a regional bioenergy network, rural regions in Kwazulu Natal could be electrified through the development of mini-grids connected to sugar mills or by engines burning locally produced biofuels.

However, there are many potential pathways possible to develop the bioenergy network. For example, centralised production of electricity would improve the efficiency of electricity production, but would require transportation of bagasse. Gasification could provide higher efficiencies than combustion, but on the other hand is a less established technology. The production of bioethanol or biodiesel could provide added economic benefits through exports, however in that case the network would not contribute to local electrification of households. It is also possible to use the bagasse to produce fuel gels (through the intermediate production of bioethanol), which could replace paraffin as the main cooking source and as such increases the health of residents working and living indoors. Each of these different pathways has advantages and disadvantages both in terms of the functionality they provide to the socio-economic and biophysical systems in which they operate, but also in terms of the different network structures that they would

⁶ At the end of 2007, one of the sugar mills installed a combustion plant to use bagasse for production of green electricity, which is fed into the existing grid.

result in. Chapter 8 will illustrate how the different functional and structural features of potential pathways can be evaluated to determine which pathways are preferred.

Eventually, the evolution of the bioenergy network will be a function of strategic behaviour of sugar mills, potential independent power or biofuel producers that enter the region, current electricity supplier, electrification plans of provinces and concessionaires⁷ and different governmental departments which are involved in the region. For example, the Department of Minerals and Energy (DME) is developing policy instruments to open up the electricity industry as well as increasing the percentage of green electricity produced, while the Department of Planning and Local Government (DPLG) is interested in electrifying rural areas. Chapter 8 will explore how different mental models can lead to different evolutionary pathways and how, within this context, it is possible to develop interventions that stimulate sustainable development of this bioenergy network.

1.5 Thesis Structure

The previous section highlighted the research questions that will be addressed in the rest of this thesis. The structure of the thesis will follow the sequential steps that are required to analyse complex adaptive systems. Firstly, chapter 2 will discuss the role and interaction of organisations within an industrial network. Subsequently, chapter 3 discusses how the emergent properties of organisational interaction can be explored using simulations models. Chapter 4 will discuss how to analyse system performance of industrial networks in terms of sustainable development and chapter 5 will discuss how to evaluate the potential evolutionary pathways of industrial networks. Chapter 6 and 7 will illustrate the methodology using a real-world case study of a bioenergy network in an emerging economy.

⁷ Currently ,three concessionaires are established in Kwazulu Natal. These concessionaires provide rural electrification through the installation of solar systems and mini-grid and in return receive a licence to supply electricity to the region.

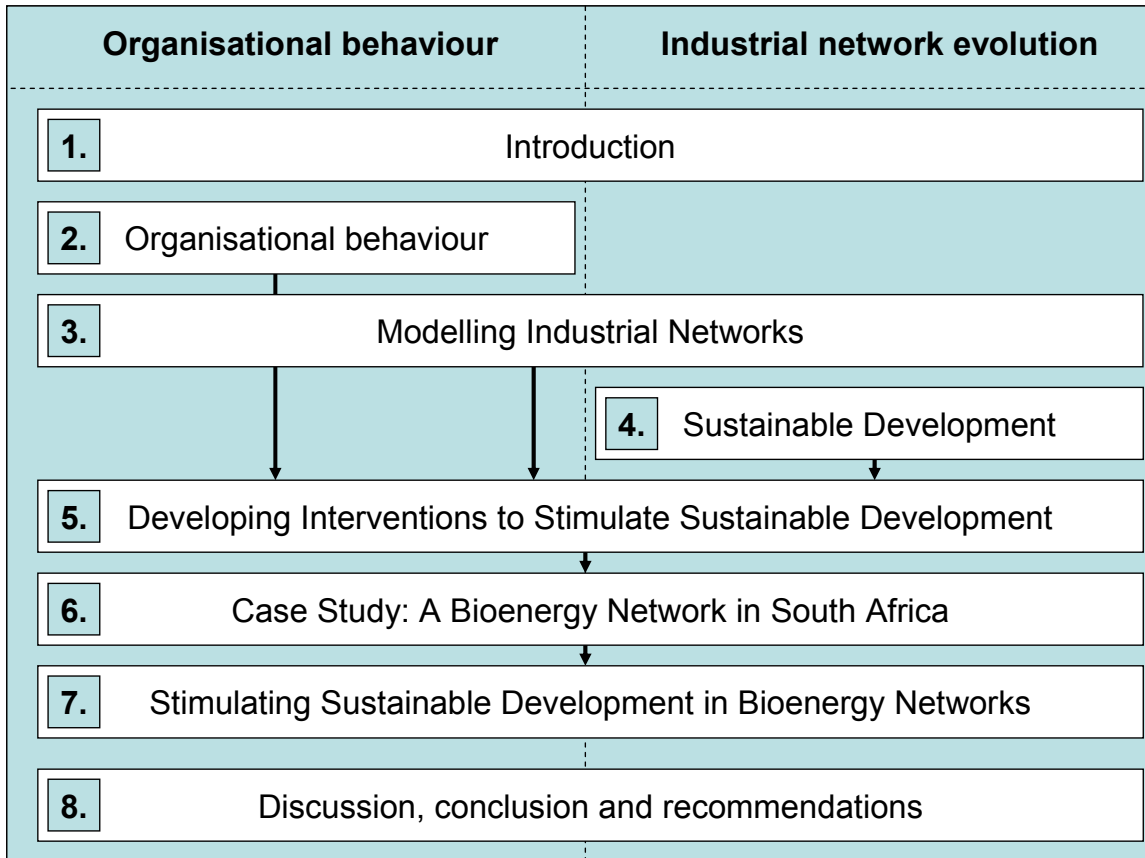


Figure 1- 4 Structure of the thesis and the relation between different chapters

Chapter 2 will develop an analytical framework in order to understand the interrelationship between organisational behaviour and industrial networks. In particular, this chapter will focus on how industrial network characteristics inform and affect decision making of organisations. On the basis of this framework, chapter 3 will propose a modelling methodology to capture the different industrial network characteristics and their impact on the strategic decision making process of organisations. Firstly, the chapter discusses a modelling format in which to capture the different interactions between organisational behaviour and industrial network characteristics. Secondly, the chapter will discuss and propose a modelling approach to interrogate the relationship between strategic behaviour on the one hand and the industrial network evolution on the other. Thirdly, this chapter will discuss several modelling tools and their potential applicability to the modelling format and modelling approach suggested.

Chapter 4 will specifically focus on industrial network evolution in the context of sustainability. The chapter will revisit the different industrial network characteristics (function, structure, governance and context) and how they can be used to characterise different network evolutions (pathways) and their contribution to sustainable development of the socioeconomic and biophysical system. The chapter concludes with the development of a set of indicators to measure and evaluate the different network evolutions possible and their potential contribution to sustainability.

Together, the analytical framework, the modelling approach and indicators for sustainable development allow for the analysis and exploration of organisational behaviour and its effects on sustainable development in industrial networks. Such exploration provides additional insights in the complexity of network evolution, information on alternative pathways that were not envisaged before and the potential to explore unexpected system properties that can arise from individual organisational actions. However, such explorations do not necessarily translate into insights in the effectiveness of interventions, since there is an unlimited number of different network evolutions possible, resulting in different performances for each intervention.

Chapter 5 discusses a methodology to systematically explore the different network evolutions possible. This chapter argues that the way in which organisations respond to uncertainty can be used as a basis for systematic analysis of potential network evolutions. It also discusses the different interventions that are possible in an industrial network and how their effectiveness can be explored in the context of complexity of industrial network evolutions.

Chapter 6 provides the background and setting for the case study of a bioenergy network in KwaZulu-Natal in South Africa. The case study has been used to develop and demonstrate the methodology to analyse and develop interventions to stimulate sustainable development. Chapter 7 illustrates how the methodology can be applied to analyse the evolution of the bioenergy network and provides case study results. Chapter 8 concludes this thesis and provides a discussion on the potential use and limitations of this methodology and recommendations for future work.

Organisational behaviour in industrial networks

2.1 Purpose and scope

The driving force for industrial network evolution is the behaviour of organisations, which, in turn, are responsive to dynamics in the network environment. Their actions determine which resources are used, how they are used, where they are used and how they are transformed into goods and services that fulfil societal needs. Organisational behaviour is determined by the resources available, the allocation of these resources between the different organisations, the number of organisations involved, infrastructure, the shift in needs from society and many other factors. An understanding of the characteristics that inform organisational behaviour is essential to understand the evolution of the network as a whole.

This chapter develops an analytical framework to capture the different industrial network characteristics that inform and affect organisational behaviour. The purpose of the framework is twofold. Firstly, the analytical framework provides a generic methodology to systematically record the different network characteristics that need to be taken into consideration to understand network evolutions. Secondly, the analytical framework serves as a platform for modelling the different relationships between organisational behaviour and industrial network evolution.

2.2 Positioning organisational behaviour

If one focuses on the position of single organisation in an industrial network, the following observations can be made:

1. they receive, provide or control resources and exchange those with others within the industrial network,
2. they have individual aims and purposes, but are inherently connected to other organisations in the network.

This chapter argues that in such situations, four different kinds of industrial network characteristics can be distinguished, which inform and affect organisational behaviour.

- functional characteristics,
- implicit characteristics on an organisational level,
- implicit characteristics related to relationships and
- implicit characteristics on a network wide social level.

The next section reviews some of the theories related to organisational decision making and different characteristics which are perceived as being important for the decision maker.

2.3 Functional characteristics

The main driver for the existence of industrial networks is resource scarcity, resulting in interaction between those organisations which control particular resources and others which require them. The notion of resource scarcity is important, because it is only those organisations perceived as having rare, valuable, non-substitutable or difficult to imitate resources, that can sustain their position in industrial networks and create competitive advantage over other organisations (Barney 1991:105-106; Dyer and Singh 1998:661). The only way to create and maintain a competitive position is to cooperate with other organisations (Hakansson 1987), hence providing the “modus vivendi” for the network. Wernerfelt (1984:172) defined resources as anything which could be thought of as a strength or weakness of a given firm, including intangible assets such as brand names, in-house knowledge of technology etc. In this thesis, however, the definition of functional characteristics encapsulates not only resources of the firm, but it covers all those

industrial network characteristics that are formalised or formally recognised within the network and that affect the position and strategic behaviour of organisations in the network. As such, functional characteristics include also those characteristics that are provided by non-industrial organisations, such as infrastructure, regulation, information and customer demand, which affect strategic decision making of organisations, their relationships and the industrial network evolution as a whole.

An analysis of the role of organisational behaviour in industrial network evolution requires an explicit consideration of the role of functional characteristics. Firstly, resource scarcity determines how, when and why organisations interact with each other. These relationships define the internal structure of the system (Manson 2001:409) and thus the efficiency and effectiveness of the industrial network as a whole (Wilkinson and Young 2002:125). Secondly, functional characteristics, and resources in particular, determine the level of control and power of organisations within the network, which affects the extent of their strategic options and those of others (Wernerfelt 1984:172; Cook and Whitmeyer 1992:123). Although Newton (Newton 2002:528) argues that these orders of power and control are always partial and temporary, affect the state of the system at any point in time and therefore industrial network evolutions as a whole.

2.4 Implicit characteristics on an organisational level

The previous section argued that functional characteristics are important inputs into the decision making of organisations and therefore industrial network evolutions. This section, however, argues that functional characteristics are not the only industrial network characteristics affecting organisational behaviour. Several researchers and research areas have argued that organisations cannot know and express the full consequences of their actions in terms of functional characteristics (Keynes 1938; Simon 1957; Cohen, March et al. 1972; Kahneman and Tversky 1979; Conlisk 1996; Thaler 2000). Therefore, organisations use implicit characteristics to inform their decision making process. The next couple of paragraphs provide an overview of the different theories that describe these implicit characteristics and how they affect the decision making of the organisation and the network evolution as a whole.

According to Bernstein (1996), modern Western society is driven by an understanding of risk and how risk affects strategic decision making. Although risk can be expressed in

terms of the expected value of a functional gain of a particular option or alternative, Bernoulli argued already in 1738 that the way in which risk affects decision making depends on the individual perspective and personal circumstances of the decision maker (Bernoulli 1954). The risk perception of an organisation is thus an implicit characteristic, not formalised within the network, but affecting the decision making of the organisation and the evolution of the network. Such implicit characteristics should therefore be taken into account while analysing the evolution of industrial networks.

The effects of individual perceptions of risk affecting decision making, postulated by Bernoulli, have also been researched and extended more recently. Kahneman & Tversky (1979) showed empirically that people and organisations are more risk averse towards losses than towards gains. In other words, organisations assign a higher weight to a potential loss than a potential gain. Furthermore, people and organisations assign higher weights to small-probability events and smaller weights to large-probability events (Maital 2004:5) Finally, the perception of risk is not only affected by the particular circumstances of the organisation, but risk perceptions are also affected by past experience (Hertwig, Barron et al. 2004:534). They found that past experience can lead to dramatically different choices in behaviour, because decision makers underestimate the weight associated with the chance of rare events (p. 537). All in all, this research suggests that risk perceptions, but also risk aversion towards losses and past experience, are important implicit characteristics that affect the decision making of organisations. Any analytical framework that attempts to capture those characteristics that affect decision making in the context of industrial networks should therefore take these implicit characteristics into consideration.

Although research on risk and risk perceptions in terms of probabilities and value preferences has a philosophical and practical foundation of hundred of years of thought (Howard 1988:679), it was not until the 1960s that researchers started to question the assumption that organisations and individual behave rationally (Gigerenzer 2001:3302)⁸. Herbert Simon was one the first who argued against the notion of rationality and he

⁸ An exception is Keynes (1938). In his book *The General Theory* he argued the following: “Most, probably, of our decision to do something positive, the full consequences of which will be drawn out over many days to come, can only be taken as the result of animal spirit – a spontaneous urge to action rather than inaction, and not as the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities” (p. 161-162).

suggested that there were many other psychological characteristics that affect the decision making of organisations (Simon 1956:137). Foremost, he argued that organisations 'satisfy' rather than optimise, suggesting that each organisation has particular 'levels' which act as thresholds and beyond which any alternative is accepted (Simon 1957:252). Furthermore, he argued that humans are limited in their computational ability to calculate the consequences of each alternative, and that their preferences are not stable, but depend on the decision situation. In the context of this thesis, then, 'satisficing' thresholds, changing preferences and computational limitations are all implicit characteristics that affect organisation's behaviour

Besides the notion of 'satisficing' developed by Simon, several other factors and processes have been identified that organisations use to interpret and understand the consequences of their actions and which subsequently affect their decision outcomes. The totality of factors and processes that assist organisations in their decision making is defined here as their mental models. These mental models play a role in two ways. First, such models assist organisations in making sense of their surrounding environment by reducing complexity through the use of information cues, assumptions, predictions, and simplifications (Sterman 1989; Weick 1995; Schein 1996). For example, organisations only use a limited number of 'cues' to evaluate their environment in complex situations (Miller 1956) or they assign particular high values to a certain event (Dawes 2000). Secondly, mental models provide a basis for the development and selection of appropriate courses of action through the use of routines, norms and values (Nelson and Winter 1982; Sterman 1989; Gigerenzer and Goldstein 2000; Thaler 2000).

Organisations use routines to link particular activities to signals out of their environment (Nelson and Winter 1982) and they pick and choose alternatives on the basis of particular attributes, rather than through thorough analysis (Gigerenzer and Goldstein 2000). Furthermore, norms and values inform the decision making of the agents affecting the outcomes of their decisions. For example, norms can discourage experimentation and support so-called lock-in situations, while values can bring shared interests or conflicts between organisations affecting their activities (March 1981:563; Thaler and Mullainathan 2000:1). The effects of the two dimensions of mental models, sense making and decision making, play a central role in the analysis of industrial network evolution, because it is the outcome of both processes that determine the

actions of the organisations. Chapter 3 will discuss in more detail the position of mental models within the computational models used to analyse industrial network evolution and chapter 5 will discuss a method to systematically analyse how the use of alternative mental models affect the evolution of industrial networks.

The implicit characteristics in mental models are not static, but they change through interaction with other organisations, through experience and learning and through changes in the external environment in which the organisation operates. However, at any point in time these implicit characteristics are necessary for any organisation to interpret the complex environment in which they operate and to process such information into actions. An analytical framework, therefore, must take these implicit characteristics into consideration as they form an important part of the decision making process of organisations and the evolution of industrial networks.

2.5 Implicit characteristics on a relational level

The previous sections discussed the functional and implicit characteristics that affect the decision making of a single organisation. However, an industrial network always consists of more than one organisation, whereby each organisation has agency: the ability to intervene meaningfully in the course of events in the system (Giddens 1984). The presence of multiple autonomous decision makers in industrial networks increases the complexity of an organisation's decision situation in two ways. Firstly, at any point in time, other organisations such as competitors or governmental organisations can change the conditions of the environment affecting the performance of other organisations. Secondly, the exchange of resources involves other organisations with individual and often unknown agendas, and therefore an organisation can, despite complicated contracts, never be certain what the consequences will be. Both processes have deep impacts on the consequences of any activities of the organisation and have to be taken into consideration. With this in mind, the theory of transaction costs has been developed, placing the transaction, rather than the organisation, as the basic unit of analysis for organisational behaviour (Williamson 1981:550).

Box 2.1 Transaction Cost Theory

Transaction cost theory is an attempt to understand interorganisational relationships from an economically rational perspective. It argues that organisational choices, especially in terms of relationships, might not seem rational in terms of maximising economic utility functions, but that this 'irrational' behaviour can be explained by hidden costs associated with finding information on the alternatives and costs associated with the transaction itself (Williamson 1981). For example, an interorganisational relationship that is perceived to lead to misunderstandings and potential conflicts requires complex contracts that are costly to write and to enforce. The transaction cost theory argues that organisations recognise these hidden costs, translate these hidden costs into functional characteristics that can be incorporated into their rational decision making process. ((Williamson 1981:553). Transaction cost theory argues thus that there are no implicit characteristics on a relational level, but that the choice between two potential partners is purely a choice on the basis of functional characteristics, such as price, quality, quantity and time. Transaction cost theory has been a very popular method to analyse organisational relationships. However, even Williamson (1993) argues that uncertainty cannot be completely reduced to hidden costs and that some relational characteristics, most notably trust, cannot be explained within the framework of transaction cost theory (Williamson 1993:453).

This section provides an overview of the different strategies that organisations employ to deal with the inherent uncertainty in interorganisational relationships. The importance of implicit characteristics in relational decisions has not been recognised in economic models of interacting organisations (Ioannides 1997). However, economic criteria, such as price and quantity, become less important than social consideration if decisions on relationships take place in uncertain situations (Haunschild and Miner 1997:479). The purpose of this overview is to identify the processes and characteristics that inform organisational behaviour in relationships and which can explain why organisations choose one partner over another. From this overview, four different categories of strategies and associated processes and characteristics are identified: 1) organisations employ different risk attitudes towards interorganisational relationships, 2) they rely on implicit characteristics such as trust and loyalty to choose between different partners and 3) they associate themselves with organisations with the same cultural values.

The role of risk attitudes in interorganisational relationships is described more prominently in game theory and agency theory. Game theory poses that the organisational decisions about others are affected by the 'added value' of the

relationship, the scope of the network, the rules of the game and the perceptions of each other (Brandenburger and Nalebuff 1996). In other words, the decision of an organisation to engage with others is affected by the resources of the other organisation, the scarcity of those resources in the context of the network, the rules that determine the conditions of a potential exchange and the perception of the organisation about the possible outcomes of the exchange. The role of perceptions is very important in this context, because the perception determines how possibilities are assigned to different potential partners and how these possibilities are evaluated in order to choose a particular action.

The perceptions and predispositions towards risk of organisations is also a central theme of agency theory (Eisenhardt 1989:62). Agency theory considers the specific case of an economic exchange relationship when one individual (the principal) grants authority to another (the agent) to act on his or her behalf, and the welfare of the principal becomes affected by the decision of the agent (Wright, Mukherji et al. 2001:3414). The second implicit characteristic that agency theory highlights is the role of the organisational norms and values. Differences between organisational goals can affect whether organisations behave opportunistic or cooperative, therefore affecting the relationships between organisations.

However, Uzzi (1997) argues that game theory and agency theory both make rather stringent assumptions about organisations being either self-interested or cooperative. Thus, although these theories accept that norms and values affect interorganisational relations, the exact role within the decision making process remains unclear. According to Uzzi, interorganisational relationships are regulated by three main characteristics: trust, fine-grained information transfer and joint problem-solving arrangements. Trust relates to norms and values as being heuristic characteristics that permit organisations to be responsive to stimuli and to speed up decision making. Trust is different from risk perceptions discussed previously, because it conforms more closely to heuristic-based processing rather than to the property of “calculativeness” that underlies risk-based decision making (Williamson 1993:469; Uzzi 1997:43)⁹. According to Sterr and Ott

⁹ Van der Ven (1994) also makes the distinction between the predictability of business risks (ie risk perception) and someone’s expectation based on confidence and expectations of ‘fairness’ (p. 93). However, according to van der Ven both dimensions describe trust. Ven, A. v. d. and R. Garud (1994). The Coevolution of Technical and Institutional Events in the Development of an Innovation. Evolutionary

(2004), mutual trust is a vital prerequisite for establishing relationships and exchanging information and/or resources in industrial networks (Sterr and Ott 2004:950). Fine-grained information exchange in close relationships is more proprietary and tacit than the price and quantity data that are exchanged between organisations without any former relationships and joint problem-solving arrangements consist of routines of negotiation and mutual adjustment that allow organisations to coordinate and resolve problems flexibly (Uzzi 1997:42-47). How these implicit characteristics can be incorporated into a generic framework to analyse the evolution of industrial networks will be discussed in more detail in section 2.7.

The fourth category of implicit characteristics that has been identified as affecting interorganisational relationships pertains to the establishment of social and/or cultural institutions. According to Henrich (2004), the degree of “pro-sociality” (altruism and altruistic punishment) observed in, and between, different organisational networks, can only be explained if the role of ‘cultural thresholds’ is taken into consideration. Cultural threshold inhibit social learning abilities, but when crossed, open new evolutionary vistas for cooperation (Henrich 2004:31). This perspective suggests that the implicit characteristics affecting interorganisational relationships are local and time dependent affected by the cultural forces that try to keep the systems in a quasi-stable equilibrium.

The overall conclusion of this section is that there are several implicit characteristics that affect decision making on interorganisational relationships. These implicit characteristics affect the decision making process significantly, and their role in the decision making process needs to be explored to gain insights in the evolution of industrial networks. The second conclusion is that implicit relational characteristics do not operate in isolation, but they are formed and informed by implicit characteristics on an organisational level and a social network level. An analytical framework of organisational behaviour in industrial networks needs to reflect the explicit role of implicit relational characteristics as well as the interaction between these relational characteristics and other levels within the industrial network.

Dynamics of Organizations. J. A. C. Baum and J. Singh. New York, Oxford, Oxford University Press: 425-443.

2.6 Implicit characteristics on a network level

The previous two sections discussed functional and implicit characteristics identified by theories that focus on either a single organisation within a complex environment or the interrelationships between two separate organisations. However, according to Uzzi (1997) the above mentioned theories ignore the issue of social embeddedness. Social embeddedness can be defined as “the extent to which economic action is linked to, or depends on, action or institutions that are non-economic in content, goals or processes”, such as underlying social network culture, politics and religion (Granovetter 2005:5).

Social embeddedness plays a role in the decision making of organisations in two ways. Firstly, social embeddedness consists of institutional behaviour that arises through strategic alliances and interorganisational networks and the associated path dependencies and organisational learning (Grabher 1993; Jessop 2001). Secondly, social embeddedness consists of societal norms and values that represent the societal context in which the economic activities of organisations take place (Polanyi 1957:54 , in Jessop 2001).

The emergence of social institutions is attributed to the cognitive ability of organisations to evaluate the performance of other organisations in the network and to assign social status to organisations depending on their short-term or long-term success (Jost 2005:1). Institutions are also formed through long-term interaction between specific organisations, through professionalism and through imitation because of uncertainty (DiMaggio and Powell 1983:150). Three different kinds of institutions are categorised: regulative (regulations), normative (rules-of-thumb) and cognitive (cultural rules) aspects (Hoffman 1999:351). Institutionalisation affects the behaviour of individual organisations in several ways: on a cognitive level, it provides guidance for making sense of the environment in which an organisation and its network, function; and on a normative and regulatory level, it provides justification for decision making and action (Schein 1990:116; Barley and Tolbert 1997:96).

Complementary to the institutional theory outlined in the previous paragraph is the structuration theory of Giddens (1984). Giddens' structuration theory is of a higher abstraction level and primarily focuses on the dynamic processes between action and institution (Barley and Tolbert 1997:93). Structuration emphasises that institutions are

not static, but can change due to exogenous forces to the system¹⁰. Giddens distinguished between three different types of institutions playing a role on a network level (institutional realm) as well as the individual level (realm of action). The institutional realm can be seen as an existing framework of rules derived from a cumulative history. The realm of action refers to the actual arrangements of people, objects and events in the network (Barley and Tolbert 1997:97).

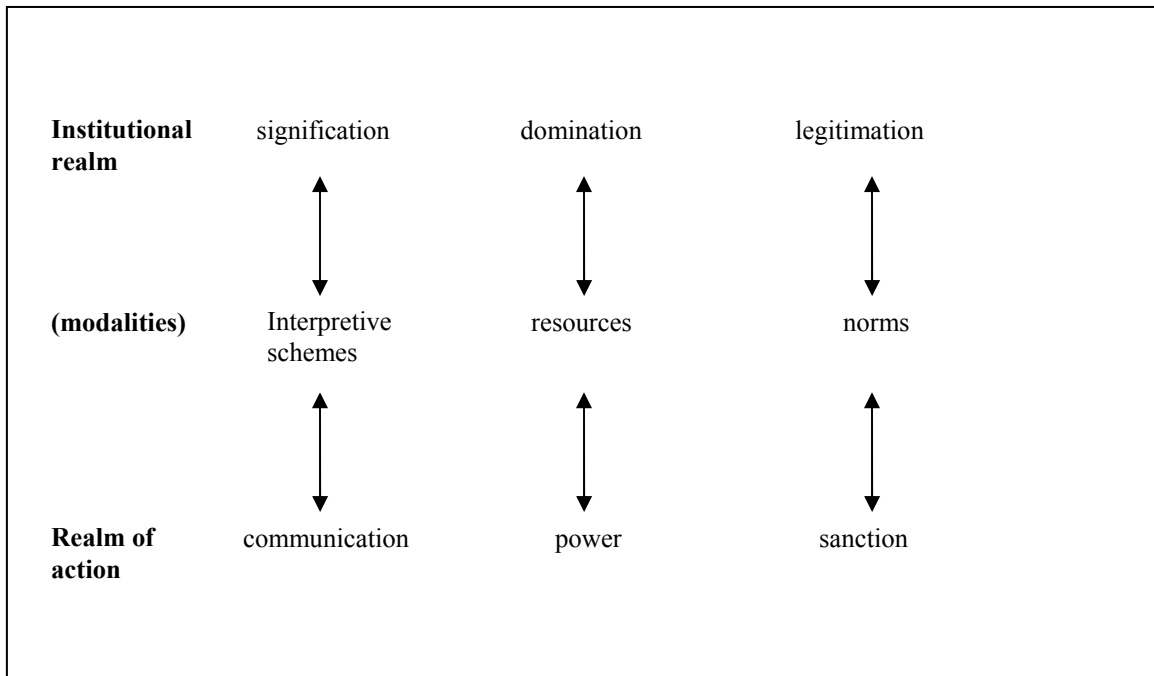


Figure 2- 1 Giddens' structuration theory (Giddens 1984)

The three typologies are signification, domination and legitimation. Signification refers to a 'shared understanding' between the agents in a structure through interpretive schemes, domination refers to control of a certain agents over other agents (authoritative) or over resources (allocative) and legitimations are the norms/rules that individuals draw on in justifying their own actions and that of others (Giddens 1984). Barley and Tolbert (1997) argue that it is empirically more fruitful to think of institutions as behavioural regularities instead of mental models or plans, while others regard the modalities rather as internalised beliefs (normative) or cognitive perceptions of "the way things are"

¹⁰ The potential for disruption exogeneous forces, ie new technologies, new regulation or laws or major economic shifts, is a characteristic of the industrial network itself and enforces market uncertainty within that particular network Barley, S. R. and P. S. Tolbert (1997). "Institutionalization and Structuration: Studying the Links Between Action and Institution." Organization Studies 18(1): 93..

(Stryker 2001:8701, original italics; Granovetter 2005:2). Domination involves the amount of power and control one agent has over other agents in the industrial network¹¹. Finally, legitimation refers to the normative aspect inherent in social practices (Li and Berta 2002:341-349).

It is not only important to recognise the effect of network institutions on individual decision making processes, but also to pay attention to the process of the establishment and change of institutions. All social actions involve structure, while all structure stems from social actions. For an organisation this implies that the structure of the network is constantly reshaped through its intentional and unintentional actions (Li and Berta 2002:342). In terms of legitimation, organisations with value systems different to those of organisations within established networks will find difficulties in entering the network, since they do not fit into the existing order. Although the process of legitimation introduces some stability in terms of entrenched structures, it also reduces the flexibility of the network as a whole by constraining its adaptability, much like any over-determined system. As such, it simultaneously creates an environment which is vulnerable to exogenous forces and which can change rapidly. In terms of the process of signification, mutual understanding between organisations increases the level of trust between these organisations and reinforces existing relationships (Uzzi 1996:692; Granovetter 2005:21). Simultaneously, however, the actions of different organisations trying to establish new order and control create opportunities for newcomers to enter networks and upset existing institutions. Similarly, in domination power relationships can only occur if one organisation does not have total control over another (Elias 1970:81). This implies that “the participants always have control over each other; in consequence, they are also always to some extent dependent on each other” (Newton 2002:529). Power relationships are therefore constantly reshaped and order is constantly changing.

The previous theories have focused primarily on social embeddedness through interorganisational interaction. However, organisational decision making is also affected through societal environment in which the organisations operate. It is in this societal

¹¹ It is argued here that power is distinctively different from status. Power is related to the importance of the organisation in terms of the resources it controls and can therefore be seen as a functional characteristic in a social context. Status, on the other hand, is not necessarily related to resources, but it is a function of the perception of other organisations in the network. Status and power are only indirectly related. An organisation that has a high degree of power is of importance to many other organisations in the network and therefore has a higher status.

environment that non-economic organisations within an industrial network affect the decision making of economic organisations and the network evolution as a whole. Those non-economic organisations, such as government, advocacy groups, workers unions or other interested parties, can impact on the development of institutions by regulative mechanisms such as jurisdiction, normative mechanism such as economic incentives or cognitive mechanisms such as supplying information, arranging protests or by organising public pressure (Kollman, Miller et al. 1997:977).

Although there is no single well-defined theory of social embeddedness in interorganisational networks, the implications for understanding the interaction between organisational decision making and network evolution is of much importance. The simultaneous actions of different organisations trying to interpret their environment and create control and order through their actions creates a dynamic environment, which is in a constant state of disequilibrium (Li and Berta 2002:342). Understanding this dynamic environment requires explicit consideration of the dynamic interaction between the implicit network characteristics that inform organisational decision making and the creating of these implicit network characteristics through individual actions and interorganisational networks. An analytical framework therefore requires explicit consideration of implicit network characteristics.

2.7 An analytical framework

The preceding discussion has identified a significant number of challenges for any analysis which aims to understand the processes that determine the complexity which defines organisational behaviour in industrial networks. Whilst these challenges are not to be understated, an even bigger one exists – and that is to define a structure within which the interplay between the salient characteristics and processes of such networks are identified and can be made operational, and the articulation of the associated information management protocols¹². This amounts to the definition of an analytical framework. Such a framework should not only reflect the associations of functional and implicit characteristics of the network, and their impact on organisational decision making, but also capture their evolution over time. A four level framework is proposed here (Kempener, Cohen et al. 2008) (figure 2-2).

¹² The specific operationalisation of this analytical framework will be discussed in chapter 3.

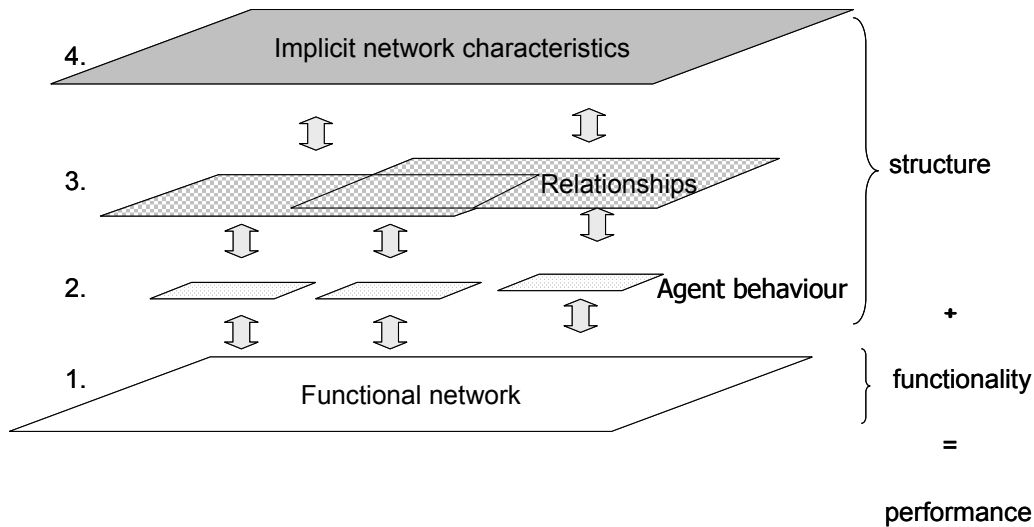


Figure 2- 2 Four Level framework for network analysis and design (Kempener, Cohen et al. 2008)

2.7.1 Level 1 – Functional level

The first level of the framework represents the functional environment of industrial networks. It describes the different resources (capital, land, labour and selected information relating to quantities of material required/available, price, delivery times, etc) that are under the control of different organisations, or available through existing relationships. Furthermore, the functional level represents the extent to which an organisation has access to information or control over resources in the network depending on its current functionality and relations, the geographical constraints, the existing infrastructure and regulation as well as other functional parameters.

2.7.2 Level 2 – Organisational decision making

The second level of the framework represents those implicit characteristics that inform the decision making processes which any organisation employs to determine transformation or exchange of resources within the network. The scientific literature reviewed in section 2.4 is well served by sources which discuss how organisations make decisions, what information they use, what assumptions they make during decision making and how they evaluate the consequences of decision in the face of complexity.

Together with the functional characteristics of an organisation, these implicit characteristics affect the behaviour of the organisation. In particular, the separate processes can be identified. Firstly, implicit characteristics play a role in organisations

efforts to make sense of and interpret their environment (broadly defined as the mental model). Secondly, implicit characteristics determine the process by which organisations translate the information they have into consequent decision strategies¹³.

2.7.3 Level 3 – Relationships between organisations

The third level of the framework represents the implicit characteristics that affect interorganisational decision making and why and how relationships are established, sustained or terminated. Section 2.5 discussed several categories of implicit characteristics that have an impact on the decision making process, such as trust, fairness, benevolence, reliability, past experience and status.

All these implicit characteristics of interorganisational relationships can be incorporated in to the third level of the analytical framework, typically by the use of proxy measures in heuristic form¹⁴. Implicit relational characteristics, like their counterparts on an individual organisational level, play a role in decisions on interorganisational relationships in two ways; some implicit characteristics are used to interpret existing and potential interorganisational relationships and other implicit relational characteristics affect the process by which an organisation decides to establish, maintain or terminate a relationship. For example, trust acts as an interpretation of the quality of a particular relationship and the level of trust might be different for each potential interorganisational relationship in the network. Loyalty, on the other hand, affects the decision whether or not to shift between existing and potential relationships and is uniquely determined for each organisation. Again, the importance of this distinction will be elaborated in more detail in chapter 5.

2.7.4 Industrial network characteristics

Finally, the fourth level of the analytical framework represents those implicit characteristics of the network as a whole that play an important role in the decision making process of individual organisations in a network evolution. Section 2.6 described research undertaken in the field of sociology and economics to describe and understand

¹³ The importance of this distinction becomes clearer in chapter 5, which describes how the analytical framework can be used to explore different network evolutions. In short, organisations use two basic processes to deal with the ignorance faced with in industrial networks. They interpret their complex environment through a simplified mental model and they use simplification procedures to convert the information into action. The degree to which they rely on these simplification procedures forms the basis for different network evolutions.

¹⁴ Chapter 3 describes how implicit characteristics might be operationalised.

the interaction between the individual decision making process of organisations and institutions on a network level.

The fourth level is of particular importance for the structure of industrial networks and how this structure evolves over time. Implicit network characteristics determine the relationships between existing organisations, which organisations are allowed to enter the networks and where there are opportunities for new organisations and/or technologies to enter the network. An analysis that takes these processes into consideration will be better placed to understand how transitions can be instigated that result in sustainable development of industrial networks.

2.7.5 Interconnectivity between different levels of the framework

Two key aspects of the structure of the analytical framework require elaboration. Firstly, the different functional and implicit characteristics that affect network evolution and functioning will not always necessarily fit uniquely into a single level of the framework, and all characteristics may play a role at various levels within the framework. For example, an organisation's routine that is identified on the decision making level of the organisation (level 2 of the framework) can be transposed to a network level (level 4) if the organisation is successful and the routine becomes a standard procedure for most organisations within the network. Secondly, the interrelationship between the different characteristics on the different levels should be highlighted. As an example, the decision to invest in a new production technology can attract a large number of new customers, which subsequently has a positive effect on the status of that particular organisation in the network, which in turn, makes the organisation more attractive to new suppliers.

2.8 Conclusion

The analysis of organisational behaviour in industrial networks is a complex problem, because organisational behaviour affects and is affected by industrial network characteristics on different levels. Economic, social and psychological studies have placed significant efforts in identifying these characteristics and relationships and how to determine the decision making process. However, most studies have only focused on one particular process, one particular characteristics or one particular level of analysis. This chapter argues that organisational behaviour in industrial networks should be analysed using an analytical framework consisting of four levels: functional characteristics, implicit organisational characteristics, implicit relational characteristics

and implicit characteristics on a network wide level. Each level contains and describes different industrial network characteristics and how these inform the decision making process. The advantage of the analytical framework is that it makes the complexity of organisational behaviour in industrial networks more transparent without compromising the ability to engage with the full complexity of the problem.

In chapter 3, the analytical framework will be used as the basis for the development of models of industrial network evolution, while chapter 5 uses the framework to develop a methodology to evaluate the effects of interventions on sustainable development of industrial networks.

Modelling industrial networks

3.1 Purpose and scope

The purpose of this chapter is to develop a modelling approach for creating an understanding of the interaction between strategic decision making and the performance and evolution of industrial networks, building on the analytical framework developed in the preceding chapter. The main reason for the development of a model is to explore the complexity of industrial networks informed by the non-linear relationship between organisational behaviour, on the one hand, and system performance on the other. A model will allow the exploration of this complex relationship, which is impossible to comprehend otherwise.

Specifically, the following research questions regarding the development of a network model will be addressed: 1) which modelling approach is most appropriate for analysing the complexity of industrial network evolution, 2) which modelling methodology can provide insights in the effects of interventions on sustainable development of industrial networks, 3) how complexity of industrial networks can be represented into a model, 4) which modelling tools are most appropriate to capture complexity of industrial networks and allow for development of intervention policies and 5) how can functional and implicit industrial network characteristics identified in the analytical framework be operationalised into a model.¹⁵

¹⁵ In the literature, the terms modelling approach, modelling methodology and modelling form are used interchangeably and are used in different ways. In this thesis, the term modelling approach relates to the question why a model is used. The term modelling methodology relates to the question how the model results are related to the research questions, while the term model form relates to how a problem is represented within the model.

The chapter proceeds as follows:

- Firstly, it will discuss different modelling approaches that can be used for industrial network evolution and how these relate to the overall objective of this thesis.
- Secondly, different modelling methodologies will be discussed and how they can be used to evaluate the role of interventions.
- Thirdly, the model form will be discussed to ensure that complexity of industrial networks can be captured therein.
- Fourthly, different modelling tools will be discussed in terms of how they relate to the different modelling approaches, modelling methodologies and model representations.
- The final section of this chapter shows the implementation of the model, in particular how functional and implicit characteristics can be operationalised.

Following on from the development of a model in this chapter, the next two chapters will discuss in more detail how the model results can be assessed and used for the development of interventions. Specifically, chapter 4 will discuss how sustainable development of industrial networks can be assessed. Chapter 5 will discuss how effects of interventions on sustainable development of industrial networks can be assessed.

3.2 Modelling industrial networks

The aim of this thesis is to develop a methodology that assists in the development of interventions that stimulate sustainable development of industrial networks. This requires a method to determine the effects of interventions on the performance of the industrial network and its evolution over time. This section will discuss different modelling approaches that can be used to determine the relationship between certain interventions (causes) and the associated changes in the sustainable development of industrial networks (effects). It is argued that simulation is the most useful modelling approach for assessing the potential effects of interventions on the sustainable development of an industrial network.

Interventions, in this context, are defined as intentional actions of one or more organisations inside or outside the industrial network to stimulate sustainable development within the industrial network. There are two broad categories of

interventions that can be thought of in relation to industrial networks: policy interventions by organisations interested in the evolution of the network; and changes in strategic behaviour by organisations directly engaged in transforming and exchanging resources¹⁶. Both categories of interventions cause changes in the industrial network. Policy interventions change the industrial network through introduction of regulation, financial instruments or information provision. Organisational behaviour changes the industrial network, because it affects the actions that take place and therefore the introduction of new technologies, material and energy streams between organisations and/or economic and social performance of the system. These changes can take place through a change in strategy or by changing the possibilities for transmission, retention and retrieval of lessons of history (March 1994:45). In industrial networks, however, the direct causal relationships between particular interventions and the impacts on the system performance and system evolution are not linear and straightforward. The sheer amount of interaction and processes taking place in industrial networks, not only between the autonomous organisations, but also between the organisations and the social processes on an institutional level, makes that the relationship between an intervention and its effects become highly complex and therefore highly unpredictable. Due to this complexity, it is impossible to determine *a priori* the impact of an intervention on the system evolution.

Testing the worthiness of such interventions by real life experiments is an almost impossible task. Firstly, it is almost impossible to isolate the effects of one particular intervention from another, especially when one takes into account that there is no single organisation that has full control in a network. Secondly, causal relationships can take many years to become evident, that is, if they become evident at all. Thirdly, the cost of failure can be high for both the intervener and industrial network as a whole.

Models provide an alternative to social experiments outlined in the previous paragraph. Models are simplifications of reality, but they can test effects of interventions before they are implemented in real life. Three broad categories of modelling approaches will be discussed; predictive models, optimisation models and descriptive models.

¹⁶ The third way in which the industrial network evolution can change is through changes in the larger system in which the system operates. However, as defined here the 'larger' system is out of control of any of the organisations' operating in or contributing to the industrial network of interest.

3.2.1 Predictive models

The most common use of modelling is for prediction. For simple systems, the predictive value of a model is high, but the predictive value of models becomes less for complex systems. The downside of increased complexity in models is twofold: 1) the interpretation becomes more difficult, which makes it more difficult to use the modelling results to create an understanding and 2) the complexity makes it more difficult to verify and validate the models. These limitations make predictive modelling not useful for the analysis of the effects of interventions to industrial network evolution.

The problem of predictive modelling of industrial networks is that it is impossible to know all relationships and variables accurately. The real-world system in which industrial networks operate is so large that it is impossible to set a system boundary for the model that represents all variables that affect the industrial network performance and evolution over time. Secondly, a large number of variables are unknown and uncertainty cannot be captured by either frequentist or Bayesian probability functions (Kay, Regier et al. 1999:728). Thirdly, large number of non-linear relationships between variables makes interpretation of modelling difficult and cumbersome (Perrons and Platts 2006:251). Fourthly, industrial networks are governed by distributed control. At any point in time, unexpected or unknown behaviour of one of the organisations in the industrial network can change the network evolution, and therefore affect predictions about the consequences of an intervention.

There are also some theoretical problems that diminish the use of predictive models for complex adaptive systems like industrial networks, especially when there is a focus on the contribution of any such interventions to sustainable development. Firstly, to understand consequences of interventions to sustainable development, a long time scale is required. Technological interventions, such as development of new power plants or infrastructure (a focus of this work), can take up to 30 years. Throughout this time, both the industrial network and its external environment evolve, and it is impossible to incorporate these external changes into a predictive model. Secondly, even if it would be possible to accurately predict the effects of an intervention, the knowledge created would change the behaviour of the organisations involved, therefore changing the course of the future. In this respect, the development of a predictive model of industrial network resembles Schrödinger's cat. As soon as a model would accurately predict the future,

the future would change and the prediction would become inaccurate. Thirdly, large numbers of non-linearities mean that small discrepancies in the initial conditions can have very large effects (studied and described in chaos theory) (Stacey 1993). Since any measurement of the real world contains an error margin, the prediction cannot be isolated from error margins in the initial values.

3.2.2. Optimisation

An alternative modelling approach to prediction is optimisation (Hall and Day 1977:9). Optimisation assumes control over a particular system and determines the system configuration that contributes most to the modeller's objective. Recent advancements in optimisation allow this modelling approach to take into account multiple objectives, dynamic external effects, and uncertainty through tools such as Monte-Carlo sampling methods and sensitivity analysis (Sahinidis 2004; Tekin and Sabuncuoglu 2004). Optimisation is mainly used for the operation and design of technical systems, but is also used for the analysis of supply chains or industrial networks (Graham and Ariza 2003; Beck, Petrie et al. 2004; Guillen, Mele et al. 2005; Beck, Kempener et al. forthcoming). In industrial network applications, optimisation tools have been successful in providing design solutions on a tactical level (Riddalls, Bennett et al. 2000:975). In other words, if one would have full control of the network, optimisation tools are useful to determine which network configuration including the activities of the individual organisations provides the best performance for the 'global controller' (see for example Shargel, Sayama et al. 2003; Paul, Tanizawa et al. 2004). However, in most industrial networks, there is no global controller and therefore also no 'single optimum solution' (Forrester 1961:section I.2). Each organisation within the industrial network has only a limited domain of control and has different perspectives on what constitutes the 'best' configuration of the network. The effect of interventions is therefore a function of responses of individual organisations, and such a situation cannot be represented at the outset within an optimisation model.

Optimisation models, however, can be part of the representation of an industrial network evolution in two ways. Optimisation models can be used to represent individual behaviour of organisations trying to achieve an optimal performance of those variables and parameters that are under their control. For example, Malan, Kempener et al. (2006) represents an industrial network whereby the individual organisations use optimisation

models to determine their desired production capacity. The industrial network evolution as a whole, however, is then again determined by the interaction between the different organisations. In this example, optimisation forms part of a simulation model and is therefore called “optimisation for simulation” (Malan, Kempener et al. 2006). The other option is ‘simulation for optimisation’. Here, the industrial network evolution is represented by a simulation model, while optimisation is used to ‘tune’ the parameters of an intervention to achieve the preferred outcome. In this application, it is assumed that the intervener has full control over the intervention and that it can optimise the format of the intervention. Both ‘optimisation for simulation’ and ‘simulation for optimisation’ can be useful in the context of industrial networks. However, both approaches rely on simulation to represent the network evolution, and it is this process of network evolution that is most important in terms of sustainable development.

3.2.3 Descriptive modelling

The third category of modelling is descriptive modelling. Descriptive modelling has been used in social and biological sciences to explain observation in the real world.

Descriptive modelling attempts to understand the patterns and processes observed in the real world by the development of theories that have a generative character; a set of principles that can explain a large range of phenomena (Epstein 2005:1). These theories can be derived in three ways; deductively, inductively; and through simulation. Deduction is used to derive new theorems on the basis of a set of assumptions, while inductive models are used to find patterns and relationships from empirical data (Axelrod and Tesfatsion 2005:4). Simulation is a combination of deductive and inductive theory development.

All three forms of descriptive modelling have been applied to industrial networks.

Deductive models of industrial networks use a set of principles or laws that explain observed patterns in industrial network evolution. For example, in a deductive model, organisational behaviour is described with a decision rule which, when implemented in a model, creates patterns observed in the real world. One of the more famous deductive models of complex adaptive systems is Schelling’s Game of Life (1971). In this model, he used an abstract system, which consisted of a number of elements that each followed a particular rule. Subsequently, he used these systems to explore how different rules can lead to different system patterns. Although deductive models are powerful means to

find general theories that can describe and explain a large array of phenomena, it is unlikely that such theory can be found for the evolution of industrial networks. Firstly, the evolution of industrial networks, as discussed in chapter 2, is affected by a large number of variables and processes and it is unlikely that a generic theory can be developed that explains all these processes simultaneously. Secondly, there is a large variety of industrial networks with each different structures, operating in different locations and involving different resources. A generic theory that explains all these evolutions simultaneously will be difficult to develop by simply observing phenomena and then trying to explain those phenomena by a set of simple rules.

Inductive models are developed through the analysis of a large number of different industrial network evolutions in order to find common patterns that would be similar for any of those evolutions. Organisational, social and behavioural sciences have used inductive approaches to isolate defining variables for specific processes within industrial networks. Their findings have been used to develop the analytical framework presented in chapter 2. However, the complexity of industrial network evolution prevents the development of inductive models for industrial network evolution as a whole. Firstly, the non-linearity between the observed patterns on an industrial network level and the actions on an organisational level prevents the development of a theory that describes all these processes simultaneously (Kay, Regier et al. 1999:728). Therefore, most theories derived in an inductive fashion only focus on particular aspects and processes within the industrial network evolution. For example, theories have specifically been developed on how organisation deal with uncertainty in their decision making, on how they choose between potential partners or how they influence and are influenced by social institutions. The second problem that prevents the development of inductive models for industrial network evolution is that industrial network evolution is affected by the larger socio-economic system in which they operate. Observations of industrial network evolution mostly take place in a particular sector over a limited timeframe (often 10 years or less)(Anderson and Tushman 1990 is an exception), which reduces the use of these observations for the development of generic theories (Knoben, Oerlemans et al. 2006).

The third way of developing descriptive modelling is through simulation (Simon and Newell 1958:6; Nance and Sargent 2002; Axelrod and Tesfatsion 2005:4; Davis,

Eisenhardt et al. 2007). Simulation starts off with an explicit set of assumptions describing relationships between industrial network characteristics and industrial network evolution. However, instead of 'fine tuning' these assumptions in order to develop a general theory of industrial network evolution, industrial network evolutions are generated on the basis of this set of assumptions. Subsequently, induction is used to relate the patterns observed in the simulating data to provide an understanding of how different network evolutions are a function of different assumptions (Epstein 1999:44; Axelrod and Tesfatsion 2005:4). In other words, simulations can be thought of as 'opaque thought experiments', that is, the consequences follow computationally implemented premises, but in a non-obvious manner which must be revealed through systematic enquiry (Di Paolo and Noble 2000:506). Carley, Prietula et al. (1998) expressed the need for a simulation approach as follows: "...no verbal theory completely specifies the mechanism let alone the dynamic unfolding process, particularly for complex adaptive systems. The simulation is needed to uncover and describe these. ...The simulation is, in essence, just another language for describing the theory." There are two ways in which the outcomes of simulation models can be used. The first method is the development of narratives and the second method is experimentally. Narratives provide information on how the future unfolds under particular assumptions. More specifically, narratives provide information about the hierarchical nature of the system, the potential states that the future can be directed to (attractors), potential flips between attractors and most important variables, parameters or feedback loops that affect the evolution (Kay, Regier et al. 1999:729). Furthermore, narratives can provide insights in how different perceptions of a particular industrial network (expressed in different descriptions) affect the analysis and understanding of industrial network evolutions. Subsequently, the increased understanding of the causal effects between perception and analysis outcomes enhances the knowledge of the decision maker (Schoemaker 1993:196). However, the use of (especially qualitative) narratives to inform decision makers heavily relies on the decision maker to extract relevant insights and to evaluate and judge the appropriateness of different perceptions. The second disadvantage of narratives is that they do not provide means for a systematic analysis of different interventions and their potential impacts on the evolution of industrial network evolutions (Lempert, Groves et al. 2006:527). If one uses simulations as experimental platforms, on the other hand, it is not the narrative that becomes the most important

output, but it is the understanding that can be created by repetitively changing input variables and observing the consequences.

The use of simulation as experiments can be related to the practice of 'reverse engineering'. Reverse engineering is used to design complex systems by starting with a particular functionality in mind and subsequently using models to work backwards to determine what could realise the physical implementation of the functionality in mind. (Chikofsky and Cross 1990). Reverse engineering requires a systems engineering approach, whereby the system property is designed (in this case the sustainable development of an industrial network) through an iterative process of exploring the consequences of different subsystems and subsystem configurations (different organisational behaviours). March (1994) has referred to the use of 'reverse engineering' to engineer the evolution of a social system as evolutionary engineering (March 1994). According to March, the aim of evolutionary engineering involves understanding social processes well enough to intervene in history and produce "a desired course of history – a vision of progress". (p. 48).

The use of simulations faces similar problems as predictive models. Firstly, like predictive models, simulations require the definition of a system boundary that represent what processes, elements and parameters are and are not included in the model. Secondly, within the system boundary there are always particular variables and processes that have not been represented within the model. Furthermore, if the real-world situations, as is the case for industrial networks, are affected by external parameters that can change in the future and are unknown, there will be no single simulation model that accurately captures all the potential network evolutions that could exist in the future. The advantage of simulations over predictive models, however, is that they these simplifying assumptions are the focus of analysis. Therefore, the use of simulation models to understand and analyse complex systems, like industrial networks, needs to be coupled to scenario analysis, whereby different simplifying assumptions about the network evolution and system boundary are modelled and compared to each other.

Scenario analysis has been developed for strategic planning and is based on the premises that there exists a plurality of different world views instead of one single truth

(Schoemaker 1993:194). Scenario analysis is particularly useful for situations under conditions of high uncertainty, such as problems related to sustainable development (Swart, Raskin et al. 2004:141). The aim of scenario analysis is to reflect a variety of world views, each resulting in a different possible future. Traditionally, scenario analysis has focused on exploring different system level contexts in which the analyst (a government, industrial organisation or group of stakeholders) might operate within the future. Such scenario analysis has been used to explore alternative futures in which governments (Chapman 1976), industrial organisations, groups of stakeholders and/or individuals might find themselves (Godet 2000; Bradfield, Wright et al. 2005).

In complex adaptive systems, however, it is not only the analyst that is faced with future uncertainty. The subjects of his/her analysis, the organisation within the industrial network, face the same uncertainty and it is their response towards this uncertainty that drives the system evolution and therefore the different alternative futures that might occur. Thus, instead of solely focusing on different world views of the analyst as discrete scenarios, the analyst should consider the different responses of organisations within the network as well. In some cases, the responses of organisations towards uncertainty might be more important for the system evolution than the uncertainty in system level parameters, because it is the response towards uncertainty rather than the uncertainty itself that drives the behaviour and therefore system evolution of industrial networks. In this thesis, the different world views that an analyst is interested in to explore are referred to as different 'context scenarios'. Within a particular 'context scenario', there are different 'agent scenarios' that reflect the different responses of organisations towards uncertainty. Each 'agent scenario' is represented by a different 'mental models', whereby each mental model represents a different decision making approach an organisation can use to deal with the sheer uncertainty that the future holds¹⁷.

¹⁷ It is important to understand and emphasise that simulations are not predictive models. The difference is that predictive models try to create outputs that reflect the real-world. Simulations, on the other hand, explore the consequences of how we perceive processes that drive real-world patterns. The use of scenario analysis has to be seen in this perspective. The agent scenarios represent different assumptions about what processes organisations use to make decisions. This distinction is fundamental in this thesis and is explored more thoroughly in chapter 5.

Table 3- 1 Nomenclature used to differentiate between an analyst's world view about the future state of a system and the potential organisational responses towards the uncertainty faced within industrial networks

Worldview	Worldviews represents the analyst perspectives on how the future might unfold.
Context scenario	Each worldview can be operationalised as different context scenarios, in which each scenario represents a different context in which the industrial network might operate.
Mental model	Mental models represent the processes that organisations adopt to deal with the sheer uncertainty they face within their strategic decision making process. Mental models determine 1) how information about the system state is interpreted and 2) how this information is used to decide upon a particular action.
Agent scenario	Within a particular context scenario, different agent scenarios can be explored whereby organisations use different mental models to respond to the system evolution.

Figure 3-1 shows how this approach to address the uncertainty associated with simulation models of industrial network evolutions might be operationalised. Firstly, a set of contexts are developed which represent the current world views of interested analysts. For the case study explored in this thesis, these different contexts can be represented by different assumptions about the need for bioenergy, future oil prices and/or population growth within South Africa. Subsequently, within each of these 'context scenarios' a set of 'agent scenarios' can be developed, whereby each scenario represents different 'mental models' used by the organisations within the network. For example, organisations that base their decisions solely on 'functional characteristics' and base their decisions on the utility contribution of each alternative use a 'mental model' in which future uncertainty is seen as manageable. On the other hand, organisations that use implicit characteristics to inform their decisions and imitate rather than optimise use a 'mental model' in which future uncertainty is unmanageable.

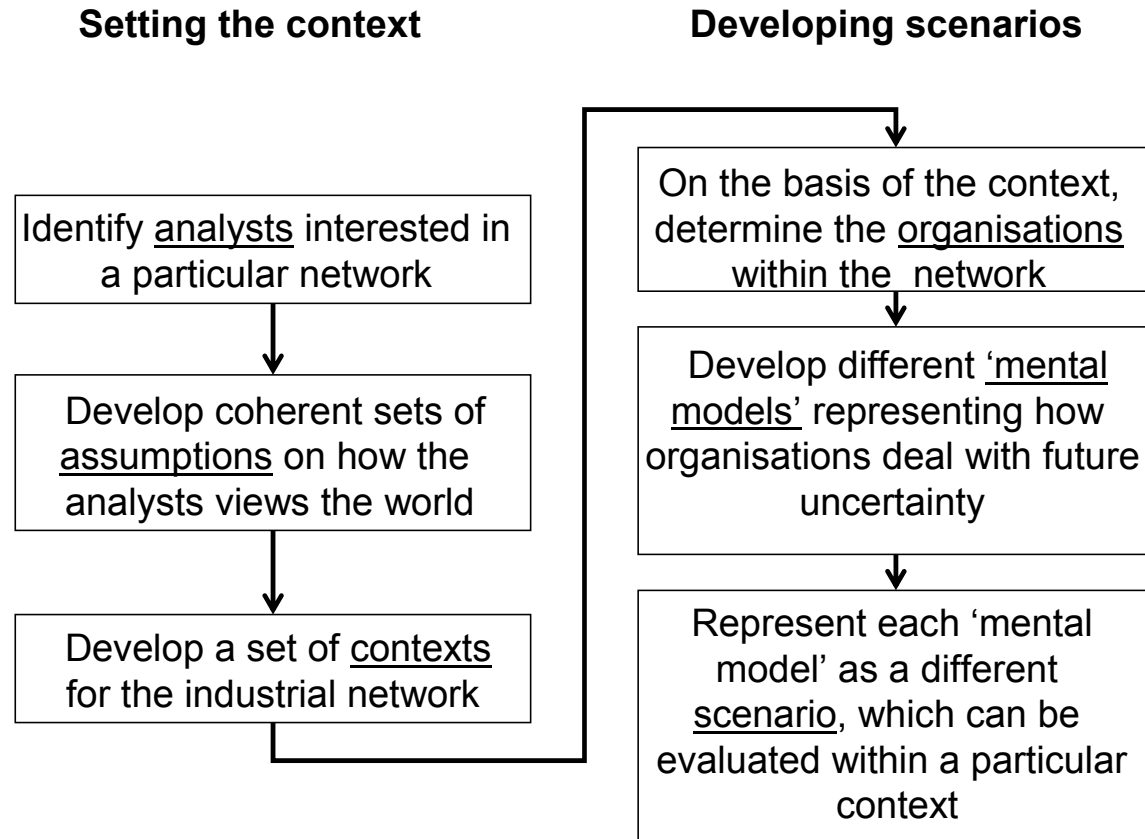


Figure 3- 1 The development of context and scenarios for evaluating the uncertainty associated with simulations of industrial networks

The use of different 'mental models' as the basis for scenarios to explore uncertainty in industrial network evolutions is a fundamental element of this thesis. The position of 'mental models' within multi-scale modelling of industrial network evolutions will be discussed in more detail in section 3.4.1. The operationalisation of mental models within a modelling tool will be discussed in more detail in section 3.6.2 and an approach for systematically exploring different mental models and their effects on the network evolution is discussed in chapter 5, in particular section 5.4.

The iterative process that is required to 'reverse engineer' sustainable development of an industrial network takes place through exploring the consequences of interventions on the system evolution under different scenarios (see figure 3-2). Each scenario represents a particular 'mental model' operating within a particular context, and, within each of these scenarios, the consequences of a particular intervention on sustainable development of an industrial network can be explored. Subsequently, the outcomes of

these explorations can be used to suggest different interventions that would perform better in terms of stimulating sustainable development. A methodology to develop a set of scenarios and compare different system evolutions to a desired evolution is explored in chapter 5.

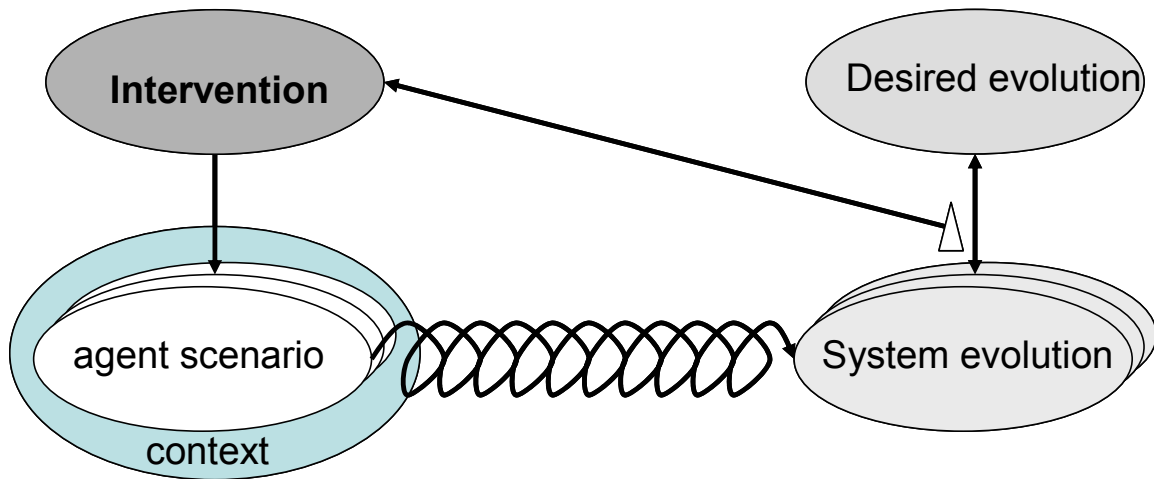


Figure 3- 2 Using simulation models to develop interventions to stimulate sustainable development of industrial networks

The use of mental models as the basis for simulations has several advantages over other methods to analyse and intervene in industrial network evolution. Firstly, simulation models do not pretend to be predictions, but instead explicitly explore the consequences of ‘sets of assumptions’ about the real world. In the context of industrial networks, these ‘sets of assumptions’ reflect the context in which the network evolves AND they reflect the mental models that organisations use to interpret the complex environment in which they operate and which informs their decision making (Forrester 1961:93; Sterman 2000:19). As such, the simulation model represents the real world by representing the assumptions that are used in the real world to make sense of, and act within, a complex environment. Secondly, simulation models can represent the distributed control present within an industrial network, because each organisation and its behavioural drivers can explicitly be taken into consideration. Thirdly, simulation allows for integrating knowledge and practices from social sciences with those of engineering. The premises that inform the simulations are derived from social sciences, while the inductive process of improving the industrial network performance is closely aligned with systems engineering practices (Jackson 1991; Phelan 1999; Amaral and Ottino 2004).

3.2.4 Model validation

The final step in developing a simulation model for industrial network evolution is to determine the validity of the model. Although it has been argued that models cannot be used to predict complex systems, the models should be able to reflect the complexity of the system under analysis. Moss (2007) presents two alternative methods for validating models of complex adaptive systems. The first method is to compare the modelling results to 'real data'. The second method is to represent the social processes driving the system evolution as perceived by participatory stakeholders (Moss 2007:2). Both methods are problematic for validation of a model that explores potential futures of a particular industrial network, especially if the analysis is over a long time scale. Firstly, there is no real data to compare the models with and secondly, the future stakeholders of the network are unknown or are not even born yet.

Yet, the purpose of many models is to explore the future and it should be possible to reflect on the validity of the models. It is argued here that for this category of models, validation should not take place by comparing the models to the 'real world', but that the validity of these models depends on the structural validity and internal consistency of the modelling process. In other words, a model is valid if the model results accurately reflect the assumptions that were meant to be explored. Forrester and Senge (1980) identified five characteristics for identifying the structural validity of a model: 1) boundary adequacy, 2) structure verification, 3) parameter verification, 4) dimensional consistency and 5) extreme conditions. The tests for validation are described in table 3-2.

Table 3- 2 Tests for model validation of system dynamics models (Forrester and Senge, 1980)

Boundary adequacy	whether the important concepts for addressing policy issues are endogenous to the model
Structure verification	whether the model structure is consistent with relevant descriptive knowledge of the system being modelled
Parameter verification	whether the parameters in the model are consistent with relevant descriptive and numerical knowledge of the system
Dimensional consistency	whether each equation in the model dimensionally corresponds to the real system
Extreme conditions	whether the model exhibits a logical behaviour when selected parameters are assigned extreme values

These tests are developed for system dynamics models, but can also be applied to models that model the autonomous behaviour of organisations within a model. The use of context scenarios to represent the analyst's world view provides boundary adequacy. The use of the analytical framework based on empirical studies of organisational behaviour provides the basis for structure verification within our modelling approach. Furthermore, the initial parameters in our models come from statistical data, stakeholder engagement and government documents. Finally, the logical behaviour of the model is tested by doing scenario analysis, whereby each context scenario represents different extremes on how an analyst views the future and whereby each agent scenario represents different extremes on how organisations might respond to future uncertainty.

The use of scenarios reflecting mental models as the basic assumptions to develop different simulation models has two advantages for model validation. Firstly, any organisational decision that is taken within the simulation model can be compared to the initial set of assumptions about the mental model. If the model is valid, each decision outcome should reflect the basic set of assumptions about the mental models of the organisations. The second advantage of using mental models as the basis for simulation models is that by using a large set of different mental models, the simulation model can reflect the decision making processes of future stakeholders. Although it is unknown who the stakeholders will be in the future, we do know that they will be faced with uncertainty

and that they will have to accommodate this uncertainty by developing mental models of their world. As such, a scenario analysis on the basis of a large set of different mental models can reflect the future better than a model that is based on the mental models of current stakeholders.

In conclusion, it can be argued that in order to create an understanding of preferred interventions for sustainable development of industrial networks, the simulation model will have to be sufficiently comprehensive to address the large range of different behaviours that organisations can display within industrial networks. This requires a methodology that systematically explores the different mental models of organisational behaviour that drive industrial network evolution. It also requires a methodology to assess and compare different network evolutions to assist in the development of preferred interventions. A methodology to assess sustainable development of industrial network evolutions will be discussed in chapter 4 and a methodology to systematically analyse different network evolutions will be discussed in chapter 5. For the purpose of this current chapter, however, it is sufficient to assume that the simulation model will have to be able to represent a large range of mental models, that their validity depends on whether the assumptions on which the model is based are made explicit, and that it will have to allow assessments of the performance of different industrial network evolution.

Finally, the overall conclusion of this section is that a simulation model is the most useful modelling approach to explore the effects of interventions on industrial network evolution. Subsequently, different agent scenarios can be developed to explore how different perspectives of organisations affect the network evolution and therefore the effectiveness of interventions to stimulate sustainable development. The validity of the models depends on how well the assumptions that form the basis of the scenario are articulated and based on empirical studies on organisational decision making. The next section will discuss different model methodologies and how they relate to the modelling approach outlined here. In particular, it will discuss the impact of different simplification assumptions on the usefulness of simulation models for developing interventions to stimulate sustainable development in industrial networks.

3.3 Modelling methodologies for complex systems

The previous section already mentioned that the development of a model requires, in one way or another, simplifying assumptions about the real-world situation that the model attempts to capture. The question that is addressed in this section is how different modelling assumptions impact on the modelling results and how one decides what modelling assumptions are required for the purpose of the model. In the context of this thesis, two requirements can be distinguished: relationship between modelling assumptions and the purpose of the model: 1) the model has to provide an understanding between particular interventions (causes) and the associated consequences for sustainable development (effect) and 2) the model has to be able to represent the complexity of industrial network evolution and its relation to sustainable development.

According to Allen (2001), different modelling methodologies can be distinguished on the different assumptions that have been made to develop the model:

1. A boundary exists between the system and the environment.
2. Objects are classified, resulting in a taxonomy of components.
3. The components of the system are homogeneous, have diversity normally distributed around the mean and do not change.
4. The collective or overall behaviour of the system results from the most probable or average processes. Or, as Allen suggests, the individual behaviour of subsystems can be described by average interaction parameters (Allen 2001:151).
5. The system moves to, or is already at, a stationary or equilibrium state. It is assumed that the relationships between variables are fixed and unchanging (Baldwin, Ridgway et al. 2004:51).

Assumptions (1) and (2) are unavoidable for the development of a model. Any model requires a system boundary and assumptions about the system characteristics. A model that uses all five assumptions is characterised as an equilibrium model, because it assumes a fixed structure and its purpose is to investigate a particular aggregate-level state (market clearing, Nash equilibrium, mass balance) and those lower level behaviours that are consistent with that property (Arthur, Durlauf et al. 1997:3). The

advantage of equilibrium models is the potential to find solutions that achieve the required system property. The disadvantage of equilibrium models is that an optimal solution not necessarily means that this solution can be achieved in practice. By assuming that variables and relationships are fixed (assumption 5), equilibrium models ignore the autonomy of organisations and the interdependence between industrial network performance and organisational behaviour. Equilibrium models are therefore not appropriate for the research questions posed within this thesis, because investigating the structural changes throughout a industrial network evolution is one of the main research questions.

If one takes into consideration that variables are not fixed, but can change over time, models can start to take into consideration change and evolution (Arthur, Durlauf et al. 1997). In the most simple case, when one assumes that the parameters in the models are fixed, this results in models that represent single dynamic trajectories into the future, corresponding to deterministic prediction (Allen 2001:152). These models are classified as non-linear, system dynamics models. "Dynamic", in this instance, refers to changes in the environment and in the characteristics of system components depending on the set of relationships between system variables. Although this class of models consists of simple linear or non-linear relationships between variables, the outcome is unpredictable and there is no set of equations which can be solved to predict the characteristics of the system (Gilbert and Troitzsch 1999:10).). Amaral and Ottino (2004) argue that it is exactly the dynamic relationships that distinguish complex systems from complicated systems and that therefore non-linear, system dynamics models can be regarded as complex (p. 1654). Vicsek (2002) supports the view that non-linear system dynamics models represent complex systems, because the relationships that govern the components of the system are different from those that describe the behaviour of the overall systems (p. 131). From this perspective, non-linear system dynamics models fulfil both requirements set out at the beginning of this section. They are able to represent the complexity of industrial network evolutions and they can be used to investigate how changes in the initial parameters of the model (ie the introduction of interventions) affect in changes throughout the network evolution.

Introducing uncertainty by representing relationships as probability functions (assumption 3) results in models that are described as 'self-organising dynamic

systems'. The term 'self-organising' refers to the emergence of different system states (system attractors) that are hidden in the system, but emerge depending on how the system evolves (Gilbert and Troitzsch 1999:1; Allen 2001:160). Relaxing the assumption that relationships are homogeneous and normally distributed introduces variety between the same class of subsystems according to their location, their objective and their history. This 'micro-diversity' is the source of multiple possible responses and can be seen as the ability to innovate, mutate or learn, allowing the model to come up with creative responses. These creative responses have been associated with the notion of evolution through accidental exploration and inherent impossibility of transmitting information perfectly. It is therefore that these models are described as evolutionary models (Allen 2001:152). Both self-organising models and evolutionary models are able to represent the complexity of industrial network evolutions and, in comparison to non-linear system dynamics models, have the ability to display different modelling results with the same initial parameterisation of the model. Although modelling results of self-organising and evolutionary models are unpredictable or chaotic, they do not necessarily reflect the complexity of real-world systems¹⁸. Instead, the representation of complexity depends on the structure of the model rather than the modelling results (see section 3.4.1). Furthermore, the use of self-organising or evolutionary models restricts the possibility to trace which particular parameter or variable within the probability range caused a particular industrial network evolution. Therefore, self-organising and evolutionary models are less useful for investigating what the consequences of interventions are on the network evolution as a whole.

¹⁸ The notion that modelling results rather than model structure represents complexity is related to different views on complexity (see box 1.1.). From the perspective of multi-scale complexity, it is the relationships between different scales of emergent properties that determine the true complexity of a system rather than the emergent properties of the system at one particular scale of observation. From this perspective, the complexity of a system should be represented by the development of a multi-scale model rather than by introducing random parameters or normal distributions.

Box 3.1 The relationship between modelling assumptions and complexity

Allen (2001) and Baldwin, Ridgway et al. (2004) have used the hierarchy of modelling assumptions to argue that by relaxing assumption (3) to (5) a progression from “simple” to “complex” modelling approaches can be obtained (p. 150). From this perspective, they argue that non-linear system dynamics models do not represent complex systems, because the future is locked into the initial setting of the model (p. 152). Furthermore, they argue that the notion of emergence in self-organising dynamic models and the notion of evolution in evolutionary models associates these two categories of models with complex systems.

However, it is argued here that the number of model assumptions is not related to complexity. In other words, complex systems do not necessarily have to be modelled with evolutionary models, while less complex systems do not necessarily have to be modelled as equilibrium models. Several reasons support this argument. Firstly, the notion of emergence is not restricted to self-organising dynamic and evolutionary models. Non-linear system dynamic models can also display emergent properties, as shown by the Game of Life or simple predator-prey models. Secondly, the classification fails to recognise that there can be a large range of complexity within each of the categories. For example, a very large equilibrium model with feedback between different subsystems can represent more complex models than simple evolutionary models. The complexity of a model is thus not only a function of the model assumptions, but depends on the scope, the number of components and the number of relationships between different scales. Thirdly, the hierarchical sequence in which the assumptions were presented is not absolute. Equilibrium models can use probability functions to describe relationships, while having static structures. Furthermore, learning can be introduced into non-linear system dynamics models in a deterministic fashion without engaging with probability functions and/or randomness.

In conclusion, this section argues that for the modelling purpose of this thesis, in which simulation models are employed to explore and develop interventions, non-linear system dynamics models are useful adjuncts. Although deterministic, these have the ability to explore the emergent features of organisational decision making, while simultaneously, each set of assumptions can be related to a particular set of emergent properties. With self-organising dynamics models and evolutionary models it is not possible to trace which particular parameter or variable within the probability range caused the industrial network evolution. Furthermore, non-linear system dynamics models provide equally well the means to capture those internal dynamics within an organisation that constitute learning, the dynamic network structures of industrial networks, and the dynamic

processes on a social level. Although it is argued that non-linear system dynamics models are most appropriate modelling method to assess the consequences of interventions to the system, self-organising and evolutionary models can augment this approach. In particular, by replacing the deterministic rules by probability functions and/or random processes, self-organising or evolutionary models allow the prospect of exploring emergent properties 'hidden' in the system. Subsequently, the non-linear system dynamics models can be used to explore which set of assumptions (or interventions) would be able to achieve or avoid these 'hidden' system properties

3.4 Model representations of industrial networks

The next step in the development of a model for industrial networks is to translate the analytical framework presented in chapter 2 into a simulation model. The challenge is that this translation process inherently requires simplification of the reality, and will never be able to represent the true complexity of the industrial network. On the other hand, a simulation model that represents all complexity is more difficult to interpret and to gain insights from. This section argues that if one takes into consideration both the system of observation and the research objective, the differentiation between different degrees of complexity within models can be made on the basis of the number of scales rather than on model assumptions.

3.4.1 Representing complexity in models

The degree of complexity that has to be represented within a simulation model depends on two factors: the research objective and the industrial network under consideration (Kempener, Cohen et al. 2007). Figure 3-3 suggests how the relative complexity of both might map onto the complexity of the model. The three axes each represent a continuum from "simple" to "complex", whereby the level of complexity is related to the Bar-Yam's definition of multi-scale complexity discussed in chapter 1.

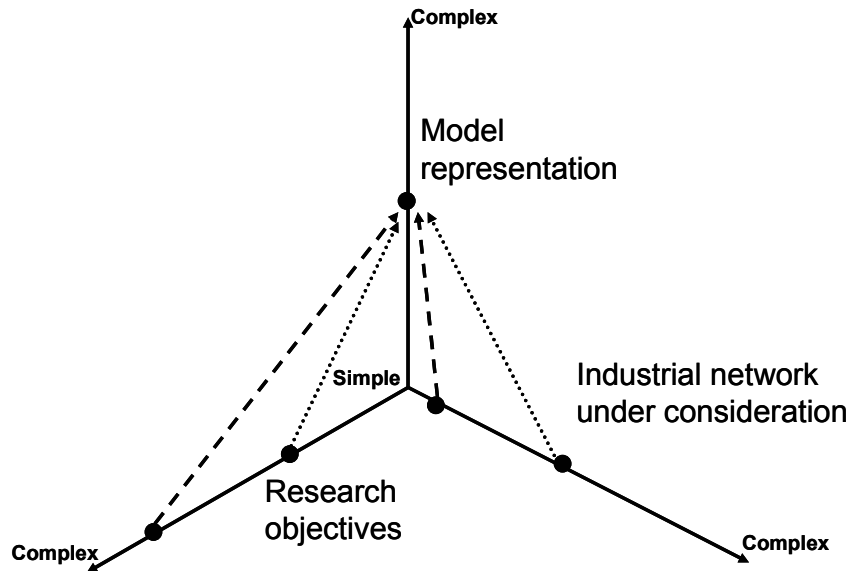


Figure 3- 3 Relationship between the model representation, the research objectives and the industrial network under consideration (Kempener, Cohen et al. 2008)

The first axis represents the research objective. Research objectives are often neglected in the development of models (Pielke 2001:5). Researchers often develop models of reality, but fail to explicitly link the form of the model to the research objectives pursued. However, it is argued here that research objectives have to be taken into consideration while developing a model. The complexity of research objectives can be characterised by the time- and space dimensions of the problem and the specific number of research objectives. For example, supply chain management is a discipline that has developed modelling approaches for industrial networks over many years. In this case, supply chain research has focused mainly on the operational aspects of supply chains, covering logistics, inventory control and production times (Yee and Platts 2006:2). Performance measures reflect short time scales of months, days or hours, and as such the external environment can be treated as static and in equilibrium. Furthermore, these analyses typically focus on only one aspect of the system, namely economic performance, while other objectives, such as contribution of the network to environmental or social welfare, are disregarded. Such an analysis would be defined as 'simple', in that the analysis takes place on a single scale, only local interactions are taken into consideration, are connected through pre-determined, and restricted time-space, represent no feedback between the environment and the system and focus on only one domain of interest. In contrast, when considering, for example, sustainable development of an industrial

network evolution, the research objective is much more complex. Analysis has to take place on multiple scales, both in terms of organisational performance as well as the environment as a whole, external effects have to be taken into consideration and the interactions between different network characteristics increase vastly.

The second axis represents the industrial network itself. Chapter 2 identified those characteristics of a network which give rise to its underlying complexity. However, the degree to which these industrial network characteristics actually contribute to the complexity of the system depends on three industrial network dimensions. The first dimension is the degree of distributed control within the network. If each organisation has limited control, the number of scales and processes that govern the system evolution increases. In particular, the interaction between implicit characteristics on an organisational, relational and institutional level increases when control is distributed. Secondly, the degree of complexity of an industrial network increases as organisations have a large array of opportunities available. In particular, if the resources and processes in the system allow for multi-purpose use, the complexity of the industrial network increases.

In conclusion, figure 3-3 suggests that neither the research objective nor the industrial network characteristics individually can determine the complexity of the model required to assess the problem. In other words, a complex industrial network does not have to be represented by a complex model and, similarly, a complex research objective does not necessarily require a complex model. However, it should be noted that the research objective and industrial network complexity are not independent. While developing a research objective the system boundary for the research problem has to be considered, whereby the boundary is determined by "how far in space or time one must go before a particular property is no longer important (Limburg, O'Neill et al. 2002:411). The definition of a system boundary has immediate ramifications for industrial network complexity, because a smaller system boundary requires fewer characteristics to be taken into consideration. The definition of the system boundary is therefore the first requirement for the development of a model (Cilliers 2001:140).

3.4.2 Multi-scale modelling

The previous section discussed how to determine the level of complexity that has to be represented in a model. It argued that both the research objective as well as the industrial network under consideration determine the required level of complexity of the model. The next step in developing a model representation is to translate the complexity of the research objective and the system under investigation into a multi-scale model.

Industrial networks are in general complex systems. The analytical framework in chapter 2 already highlighted the large number of variables and relationships that affect strategic decision making of organisations and therefore the evolution of industrial networks. To represent the complexity of industrial networks into a model, a multi-scale model is required that relates processes at one scale to emergent properties and processes at other scales. Both, complexity in the system under investigation and complexity in the research scope, are reflected by the number of scales within a model. Firstly, complex systems are characterised by multiple scales or so-called 'multiscalarity' (Abbott 2007:11), whereby properties on a systems scale emerge from the interaction of its subsystems on a finer scale. Secondly, complex research objectives are multi-scaled, because they address multiple aspects often ranging over different time scales and spatial scales. On this basis, the number of scales within a model is a better indicator for the usefulness of a model for complex systems both in terms of system representation and research objectives than the number of model assumptions (see the discussion in section 3.3).

For industrial networks, a four-scale model is developed, as represented in figure 3-4.

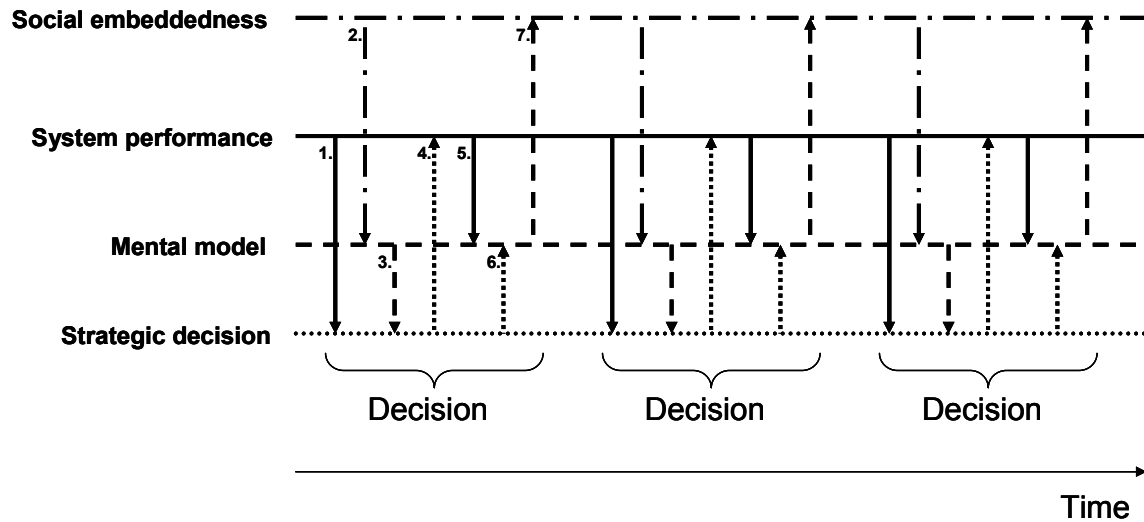


Figure 3- 4 Simple representation of the four-scale model of industrial network evolution

The model consists of four scales, each with different dynamics affecting properties at other scales in the model. The four scales are:

- 1) the strategic decision making process of individual organisations within the network,
- 2) their mental models, and how they perceive the world,
- 3) the industrial network as a whole, and its performance in terms of function and structure, and
- 4) the processes that govern the social embeddedness of organisations.

Although figure 3-4 represents the interaction between the different scales in a linear and sequential fashion, the model has interaction between the different scales at any point in time depending on what each organisation is doing. However, for each decision the different scales can interact in seven different ways. The state of the industrial network affects the strategic decision making processes of an organisation (1). Furthermore, how the state of the industrial network affects the strategic decision making process depends on the mental model of the organisation (3) and how these mental models are affected by social embeddedness (2). The outcome of the strategic decision making process affects the state of the industrial network (4), whereby the consequences of the actions are used to update the mental model either passively (5) or actively (6). Finally, changes in the mental models affect the development of new social institutions (7). Although not all processes will be carried out in a decision making

process, or multiple feedback loops might occur within each decision making process, the multi-scale representation provides the possibility to model the complexity of industrial network evolution, especially when overlaid on the network analytical framework developed in Chapter 2.

Where the analytical framework describes the different characteristics of an industrial network, this multi-scale framework describes the different processes that inform and change these network characteristics over the course of a network evolution. The strategic decision making process is modelled as a separate process, because it involves an instantaneous impulse (ie the action) that affects industrial network characteristics on all the other levels. This decision is informed by the mental model. The mental model determines which information about the system informs the decision making (the sense making process discussed in section 2.4) through the use of norms and values that change over time through learning and it determines which cognitive processes are used in the decision making process on the 'strategic decision scale'. Furthermore, the processes on the scale of the 'mental model' determine which social norms and values might be used within the individual organisation. The 'mental model' scale has thus a central position within the multi-scale model of industrial networks and the different processes that inform different 'mental models' have an important impact on the network evolution. It is therefore that section 3.2.3. argued that different sets of 'mental models', based on different perceptions about future uncertainty (the set of different 'mental models' is developed in chapter 5), should form the basis for a scenario analysis. The system performance is modelled at a separate scale, because its dynamics depend on the actions that are taken. These dynamics are different from the actions that individual organisations take, because some actions of individual organisation can have long-term effects, while others do not have an impact at all (ie an organisation that decides to defer an investment until a later stage). The fourth scale is the dynamics of social embeddedness. These dynamics, as discussed by DiMaggio and Powell, are informed by the interaction between organisations and depend on the building up of mutual trust between interacting organisations (DiMaggio and Powell 1983:148).

As argued previously, the four-scale model should not be confused with the four-level analytical framework presented in chapter 2. The latter has been developed to

characterise different industrial network characteristics that impact on the decision making processes of organisations in industrial networks. At any point in time, the analytical framework describes the state of a system. The multi-scale model, on the other hand, represents the different processes that take place, whereby each scale represents different dynamics affecting the industrial network characteristics. For example, the scale of strategic decision making represents the actions that are taken and affect the network evolution. The scale of the mental model represents the processes that involve functional and implicit organisational and relational characteristics, and how these are used in the decision making process. Similarly, the level of social embeddedness uses both functional characteristics (ie the structure of the network) as well as the level of trust between organisations (implicit relational levels) to inform the process of institutionalisation.

The research objective of this thesis, the relationship between organisational behaviour and industrial network evolution, also relates to this four-scale model of industrial network evolution. In particular, the model allows for assessing how interventions at any of the scales (either in the system through the development of infrastructures, in the strategic decision making process through regulation, or in the mental models through the provision of information) affect the interaction between the different scales and therefore the industrial network evolution as a whole. A multi-scale model is therefore extremely pertinent to the research question.

In conclusion, this section argues that a model for exploring the relationship between organisational behaviour and industrial network evolution, with the intention of developing interventions that stimulate sustainable development, benefits from a multi-scale non-linear system dynamics model. Such a model represents the complexity of industrial network evolution, and simultaneously provides the opportunity to explore the effects of interventions under different scenarios of 'mental models', whereby each 'mental model' represents a different set of processes that reflect a particular perception towards uncertainty. The model can be expanded by introducing probability functions and random processes in order to explore 'hidden' system properties, which are useful for the development of different interventions.

3.5 Modelling tools for industrial networks

In the previous two sections it has been argued that to explore and develop interventions to stimulate sustainable development within an industrial network, multi-scale simulation models with non-linear system dynamics features is most useful. This section will discuss several modelling tools that are available, and their appropriateness for developing the sort of models outlined previously. This section will develop a list of methodological requirements and will then compare the different modelling tools with each other. It is argued that an agent-based modelling approach for modelling organisational behaviour, augmented with system dynamics models for modelling social processes, addresses all the requirements.

3.5.1 Overview of modelling tools

There is a vast array of tools and techniques available that attempt to assist analysts and decision makers in exploring the future. Porter, Ashton et al. (2004) mention around 60 different methods that can be used to explore different technology futures - ranging from soft methods using creativity workshops to quantitative tools involving statistical analysis (Porter, Ashton et al. 2004:290-291). Of particular interest for this thesis are those tools that can provide insights into complex interactions between autonomous organisations over a long time, and which can assist in the assessment and development of interventions against the stated objective of sustainable development. Furthermore, it was argued that a model should include multiple scales with feedback between the different processes that take place. Only quantitative models can explore these multiple interactions and processes over a long time range.

From this perspective and given the needs previously articulated, the following requirements can be extracted:

- a) The modelling tool should be quantitative to be able to explore the complex interactions between organisational behaviour and industrial network evolution over a long time frame
- b) The modelling tool should be able to explicitly consider autonomous behaviour of organisations.
- c) The modelling tool should be able to represent the diversity of individual organisations.

- d) The modelling tool should be able to represent implicit characteristics quantitatively.
- e) The modelling tool should handle both discrete and continuous processes.
- f) The modelling tool should be able to be based on logic.
- g) The modelling tool should allow for the introduction of probability functions and/or randomness to explore 'hidden' system properties.

In terms of quantitative modelling tools, there has been dramatic advancements in computational power and mathematical tools available (Pielke 2001:3). Mathematical models applicable for industrial networks have been developed in disciplines ranging from economic sciences, sociology, ecology, operational research studies, engineering sciences to information and computing sciences. Examples are bottom-up and top-down models developed of sectors and economies in economic studies (Jacobsen 1998; Rivers and Jaccard 2005), sociometrics in sociology (Anonymous 1937; Edling 2002), discrete events, inventory and queuing theory models in operational research (Winston 1994), process systems models in engineering (Casavant and Cote 2004; Sargent 2005) and system dynamics models in ecological and management sciences (Forrester 1961; Costanza, Duplisa et al. 1998; Sterman 2000).

However, most models in economic and organisational sciences focusing on industrial networks have used this extended computational power to develop larger predictive and deductive models rather than models that explicitly deal with the interaction between organisational behaviour and industrial network evolution (Wellman, Frank et al. 1991:223; Anderson 1999:229). Instead of reviewing the advantages and disadvantages of different modelling techniques in each of the disciplines, this thesis takes a more pragmatic approach. It argues that, as long as the modelling technique can fulfil the requirements stated previously, any modelling tool is useful for modelling organisational behaviour in industrial network evolutions. Thus, instead of advocating a particular modelling tool, it argues for a particular modelling concept.

From this perspective, agent-based modelling (ABM) is an interesting modelling tool for modelling of organisational behaviour in industrial networks. ABM does not presuppose a particular modelling technique, but advocates a modelling mindset (Bonabeau 2002:7280). Agent-based models consist of a collection of autonomous decision makers

that interact within a common environment. These decision makers assess their situation and, if perceived necessary, interact with other agents and/or the environment to change their situation into a more preferred one. As such, any agent-based model is a multi-scale model with agent behaviour at one scale and system evolution at a higher scale. The rules by which they decide to act may vary and range from very simple to complex optimisation rules. An important point is that the implementation of these behavioural rules can be implemented using different techniques as long as the rules describe the dynamics of one of the system's constituent units (Bonabeau 2002:7280). For example, differential equations traditionally used in system dynamics models can also form the basis of an agent-based model.

A representation by Jennings (2001) highlights the special features of ABM (figure 3-5). The agents are autonomous and diverse, but operate in a common environment. Furthermore, the sphere of visibility and influence of each agent is limited, which in industrial networks represents the mental models that agents use to interpret their environment and make decisions. Figure 3-5 also shows how ABM represents hierarchical structures of agents. For example, employees can be represented as agents, which form together a business division. Subsequently, the business division can interact as a single agent with other agents in the network. Finally, figure 3-5 shows how agents need to interact with each other to secure the resources they need to survive in the network and to keep the system running.

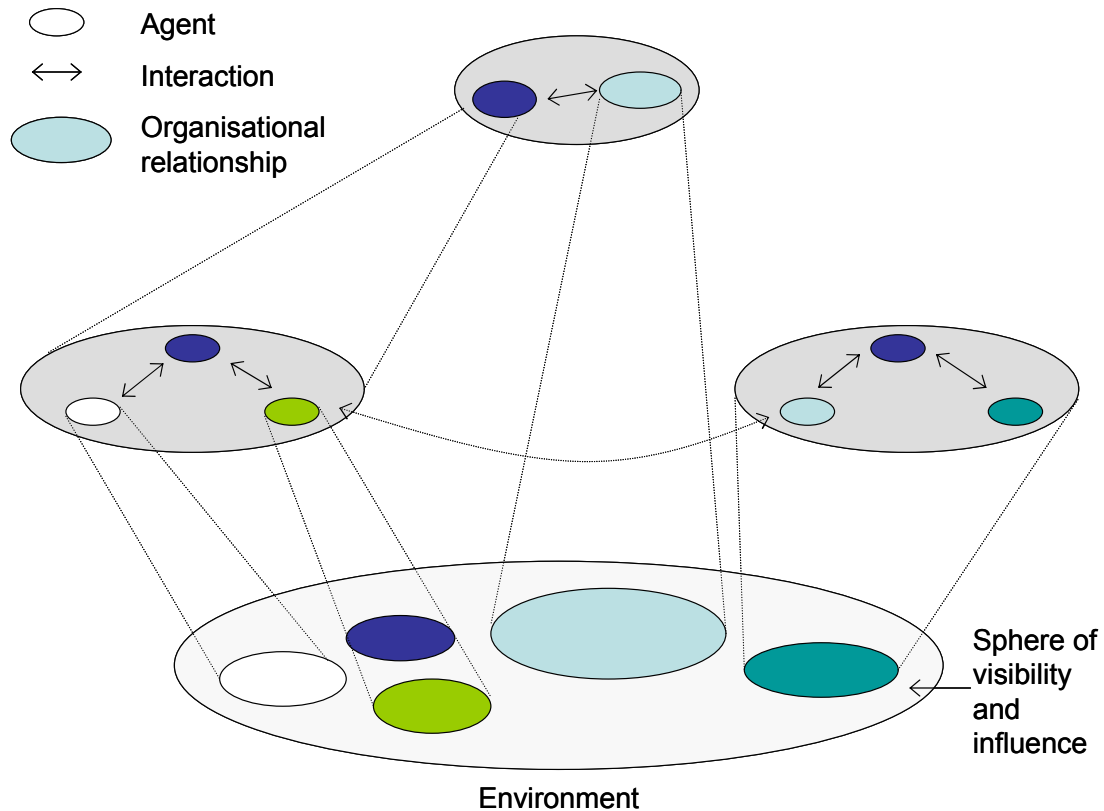


Figure 3- 5 Canonical view of an agent-based model (Jennings 2001:37)

Modern ABM originates in computing and information sciences, although the concept of modelling individual behaviour for socioeconomic studies was already suggested by Orcutt in 1961 (Orcutt, Greenberger et al. 1961). At that point in time, however, it was seen as a predictive tool constrained by computational power rather than methodological challenges (Orcutt, Greenberger et al. 1961:399). Since then, however, there have been a lot of different applications of agent-based modelling to industrial networks. ABM has been used as an engineering solution to large, open and interconnected information environments, whereby agents are robots that control particular parts of the environment and communicate with each other (Huhns and Singh 1997:1). Examples of this application are ABM used in traffic control or production systems. Furthermore, ABM has been used to explain and predict the evolution of evolving systems of interaction agents, such as stock markets, innovation diffusion, electricity generation bidding systems and other socio-economic phenomena (Epstein 1999; Gilbert and Troitzsch 1999; Tesfatsion 2001; North, Conzelmann et al. 2002). In these cases, the computational agents are embedded with different theoretical behavioural rules or with behavioural rules observed

in real-world experiments that reproduce observed or predict future patterns in socio-economic systems (Axtell 2000). A third strand of researchers uses ABM to develop and advance theorems (Schelling 1971; Arthur 1994; Edmonds 1998). Rather than focusing on reproducing observed phenomena, these researchers use ABM to explore the consequences of simple rules of interaction on system wide patterns¹⁹.

ABM as intended in this thesis is a combination of these three application areas. The agents are endowed with different mental models, represented by set of theoretical behavioural rules reflecting their perception towards uncertainty, to explore the effects on industrial network evolution. However, the observed patterns in the network evolution are not compared or used to predict, but instead are used to evaluate the different 'mental models' against each other. Subsequently, these insights are used to suggest and develop interventions that result in system patterns that stimulate sustainable development.

Bonabeau (2002) mentions three advantages of ABM: 1) it accommodates non-linear relationships, involving step-changes and "if-then-else" rules, commonly used in organisational decision making; 2) it models industrial network evolution from the perception of individual decision makers and 3) it is flexible enough to explore a range of different mental models and their effects on the network evolution (Bonabeau 2002:1780). These advantages are partly related to the use of object-oriented programming in ABM, which facilitates the possibility to represent large systems and allows for the use of linguistic models as well as mathematical models, which enhances the flexibility and logical consistency of the models (Holland and Miller 1991:6). Furthermore, Tesfatsion (2002) argues that ABM is useful, because it explicitly deals with the two-way feedback between microstructures and macrostructures (p. 264).

Another advantage of ABM, particularly in the context of sustainable development, is that it can be combined with other analysis and evaluation tools for developing interventions. Boulanger & Brechet (2005) conducted a comparison between different modelling tools and their usefulness for policy-making in sustainable development. They listed common problems associated with sustainable development (ie temporal, spatial and social externalities) and the associated methodologies to address these problems

¹⁹ See the discussion on deductive modelling in paragraph 3.2.3.

(Boulanger and Brechet 2005:339). Subsequently, they used a “goodness-of-fit” test between different modelling tools and methodologies that have been used to address complex issues in sustainable development. The 5 methodologies were:

- a) interdisciplinary approach,
- b) uncertainty management,
- c) long range view,
- d) global-local perspective,
- e) stakeholder participation.

Their findings suggests that ABM is more useful than other modelling tools, such as macro-econometric models, general equilibrium models, optimisation models, Bayesian network models and system dynamics models. More than these other modelling tools, ABM allows for the spatial and natural setting of organisations; for participatory approaches whereby different stakeholders can explore different sets of assumptions; and by explicitly representing relationships on different scales of analysis (Boulanger and Brechet 2005:349).

However, there are also some critiques on the use of agent-based modelling approaches. One of the main critiques is that ABM are based on an individualistic view of the social world, ignoring the pre-existence of culture, and failing to capture social institutions and structures as independent processes external to agents (O'Sullivan and Haklay 2000:1416). Furthermore, some research argues that object-oriented programming is too limited to represent complex systems (Jennings 2001:39). Finally, Axtell (2000) argues that one significant disadvantage of ABM is that it is impossible to develop robust theorems, because there is no definite set of parameter space that can be explored to check for robustness (Axtell 2000:3).

These disadvantages need to be considered if using ABM for modelling industrial network evolution. Social embeddedness is an important issue within industrial networks (see section 2.6) and institutionalisation processes cannot be attributed to individual agents. Changes in the environment of the organisations are thus not only a product of agent behaviour, but involve processes external to the agents. Borshchev (2005), argues , therefore, for multi-approach modelling, whereby ABM tools describing organisational behaviour are combined with system dynamics tools that describe

processes within the environment. Such an approach is also suggested here for the modelling of organisational behaviour and industrial network evolution in this thesis. Furthermore, a purely ABM approach might be too restrictive in circumstances where object-oriented approaches cannot capture the complexity of organisational structures. For example, an organisation might have different functions in different environments.

Finally, ABM, even if combined with other modelling approaches, does face the difficulty that modelling results are instances of the specific parameters that form the basis of the modelling tool. It is therefore necessary to develop a methodology that provides confidence that the modelling results are robust. The challenges involved in developing such methodology have already been highlighted in section 3.2. and the interaction between 'context scenarios' and 'agent scenarios' will be discussed in more detail in chapter 5.

In conclusion, this section argues that ABM augmented with other modelling tools to account for industrial network processes external to agents allows for the modelling of organisational behaviour and industrial network evolution. The modelling techniques can vary as long as they are quantitative of nature, support multi-scale modelling, allows for non-linear relationships and uncertainty analysis.

3.6 Operationalisation of an industrial network model

This final section of this chapter describes the process by which organisational behaviour and industrial network evolution is encoded into a multi-scale, non-linear, agent-based system dynamics model. In accordance with the previous discussions in this thesis, the following list of explicit model requirements is developed:

- a) model how agents make strategic decisions
- b) take into account how mental models of agents inform their decision process and actions
- c) take into account the relationship between mental models and the environment in which agents operate
- d) include the relationship between mental models and social embeddedness
- e) include how agents' actions, in particular the establishment or termination of relationships, affects system performance

- f) include how social embeddedness affects, and is affected by, the establishment and termination of relationships.

To accommodate these requirements, the following approach is taken. Firstly, the different industrial network characteristics and processes, identified in chapter 2, are represented into a generic four-scale representation of industrial network evolution. The starting point is a model of the strategic decision making process of organisations, which is represented as generically as possible to allow for exploration of different strategic decision making processes. Subsequently, the different industrial network characteristics that could affect organisational behaviour and network evolution are represented in the model. These industrial network characteristics and their relationships can be adjusted to accommodate modelling a variety of theories on organisational behaviour. Secondly, the system performance is modelled in such a way that it allows for an integrated evaluation of sustainable development of the industrial network.

The first section will discuss the development of a generic model for strategic decision making. The second section will discuss how different industrial network characteristics can be represented within the model. This will take place in three stages; 1) the representation of industrial characteristics on an organisational level, 2) industrial network characteristics on a relational level and 3) industrial network characteristics on a network level. The third section will discuss how the system performance has to be modelled to allow for an evaluation of sustainable development.

3.6.1 Modelling strategic decision making

Strategic decision making can be seen as a 'set of consistent behaviours' concerned with the match between internal capabilities of an organisation and its external environment (Ansoff 1965:5; Mintzberg, Raisinghani et al. 1976:256; Mintzberg 1978:941; Hakansson and Snehota 1989:188; Itami and Numagami 1992:119; Kay 1999:2). As such, strategic decision making determines the course of the entire organisation through time (Eisenhardt and Zbaracki 1992:17; Porter 1996:64). Strategic decision making can take different forms. Moss (1981) identified three different categories of strategic decision making (ch. 1):

- investment strategies: technological research and innovation, product diversification and horizontal or vertical integration;

- exchange strategies;
- competitive strategies: price-cutting strategies or non-price competition by advertisement, customer-service etc.

From a sustainable development perspective, this list of strategic decisions can be expanded. Organisations can decide to get involved in community projects, set up charities or other activities on the banner of corporate social responsibility (Korhonen 2003; Porter and Kramer 2006). Furthermore, innovation activities and supply chain activities can be undertaken, either driven by economic concerns or by sustainable development concerns.

From an innovation point of view, the list of potential strategies can be expanded by activities, such as entering or exiting a market, investing in new production technologies building new manufacturing capacity or forming strategic partnerships (Eisenhardt 1999:70). This list of strategic activities can be expanded if one specifically focuses on strategic behaviour in industrial networks, whereby decisions on close or arm-length relationships can reposition organisations in terms of resource availability and/or level of control versus freedom (Hakansson and Ford 2002:134).

This list of strategic activities is by no means exhaustive. Of importance is that any of these decisions changes the production and exchange of goods and services between different organisations in the network now and in the future. These changes, subsequently, affect the interdependencies between organisations and the co-evolution between organisations and network institutions (Hodgson 1988:358; Grabher 1993; Gadde, Huemer et al. 2003). A model of strategic decision making has to be able to accommodate the constant interrelationship between strategic actions and changes in the external environment.

From a modelling perspective, it is therefore important that there is an explicit relationship between strategic actions of organisations and their consequences for the external environment in which they operate. Several researchers have developed models and theories that describe strategic decision making in organisations. Some of these models are descriptive, while others are prescriptive. A comparison of ten different models on decision making by Basson (2004), reveals that both categories of models

distinguish at least three stages (p. A-3). The first stage deals with recognition of a decision situation, followed by some form of design stage whereby alternatives or options are identified and a final stage which involves the decision itself. Of the descriptive models of decision making, Mintzberg, Raisinghani et al. (1976) developed one of the formative, and most elaborate models of strategic decision making. Mintzberg, Raisinghani et al. build on work of Cyert, Simon et al. (1956), which observed that strategic decision making in organisations does not follow the rational choice process. The sequence of decision making processes is not clear, alternatives are not given but need to be sought or developed, and the consequences of decisions are almost always unknown or information about them is incomplete (Mintzberg, Raisinghani et al. 1976:251). Furthermore, these authors realised that the decision making process is not linear, but involves many feedback loops and non-linearities without following a predescribed programme (p. 246).

In comparison, prescriptive models of strategic decision making advocate a much more linear approach whereby objective and criteria are known at the outset, alternatives are identified and decomposed in terms of uncertainties and preferences, and decisions are implemented (Clemen 1996; Keeney 1996). Although the latter models of strategic decision making are easier to translate into formal quantitative simulation models, they would do injustice to the complexity of the decision making process in the real-world. Therefore, this thesis adopts the strategic decision making model of Mintzberg, Raisinghani et al. (1976) as the basis for the development of a simulation model.

Their model (figure 3-6) was based on four different stages identified in the work of Cyert, Simon et al.: identification, development, evaluation and selection. However, they extended this observation in several ways, some of which are important in the context of modelling strategic behaviour of organisations in industrial networks. One of the important observations of Mintzberg et al. was that the moment of action was not often the appearance of a distinguished problem, opportunity or crisis, but that the determining factor could be viewed as the relationship between cumulative amplitude of stimuli and an action threshold (p. 253). For example, the need for an industrial organisation to improve the working circumstances of their employers might only become apparent after a number of accidents have taken place. In this example, the organisation only recognises a problem after it harmed its employers. Furthermore, the amplitudes of

stimuli are not static, but depend on the decision maker's interests, the influence of its source, the perceived payoff of taking action, the uncertainty associated with the stimuli as well as the perceived successfulness of the decision. For example, the awareness of the environmental and social consequences of strategic actions have become more apparent to organisations now that shareholders have become interested in these subjects.

The second important observation is Mintzberg et al.'s characterisation of different strategic decision processes within a single model (p. 268-273). They identified 7 different types of strategic decision making processes with increasing complexity. The most simple strategic decision making process only involves a single proposed action, without any development activities, and where the outcome is a single go/no-go decision. The most complex processes are dynamic design processes involving relatively large investments, complex design activities and the likelihood of new options interrupting the process, which stretched the processes over more than one year.

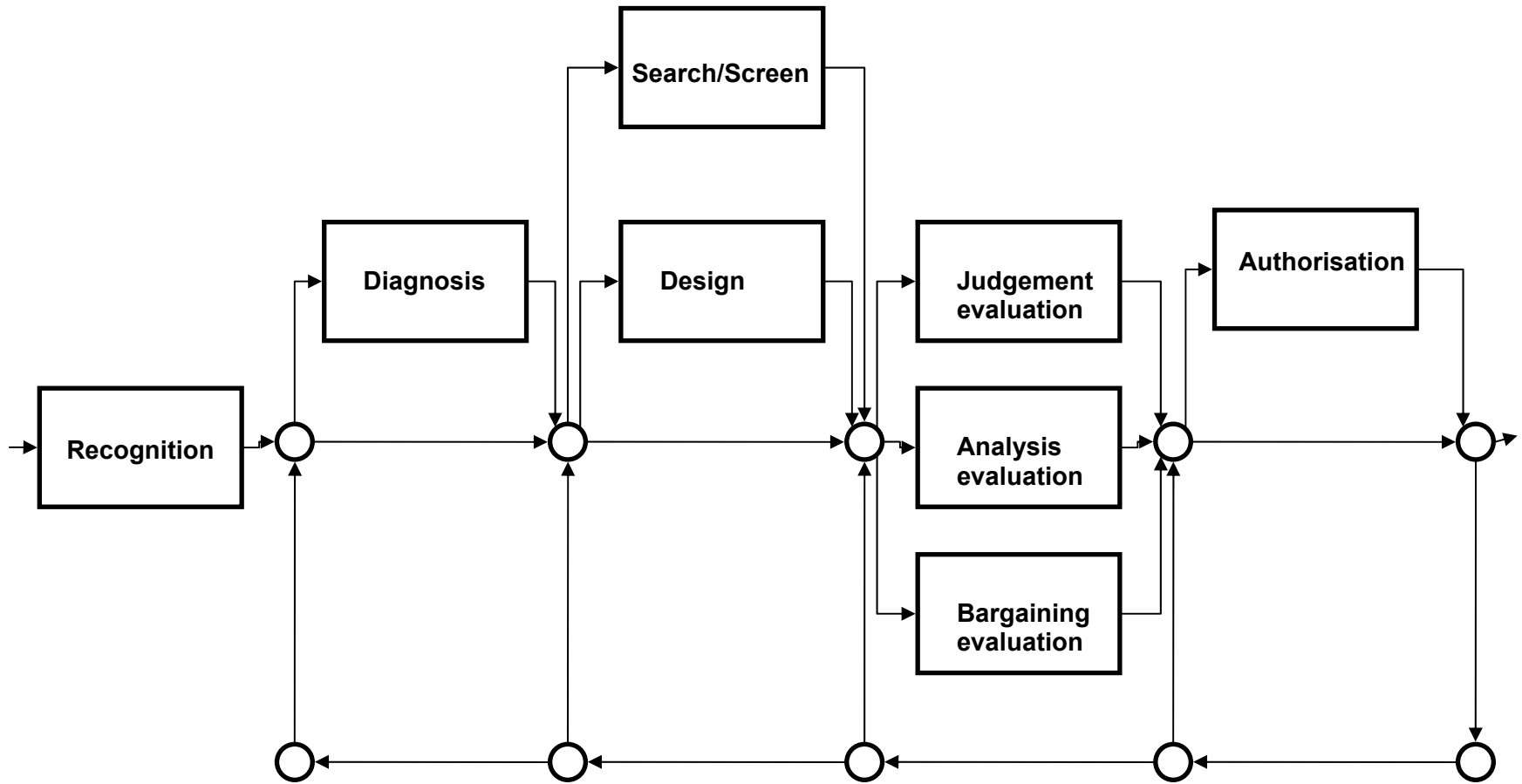


Figure 3- 6 General model for strategic decision making in organisations (Mintzberg, Raisinghani et al. 1976:266)

These observations coincide with literature that discusses the role of cognitive processes in 'mental models', their role in reducing sheer ambiguity that organisations face and their impacts on the outcome of a strategic decision making process of an organisation. The decision making model by Mintzberg et al. displays these different cognitive processes, from simple routines to complex multi-objective optimisation rules, and allows for modelling the effects different cognitive processes on the decision outcome and their network evolution as a whole. For example, a simple routine is represented as a straight relationship between the recognition of a stimuli and a judgement evaluation, while the use of multi-objective optimisation rules follows different cognitive process from recognition, to diagnosis, to search and screen activities to analysis evaluation (see figure 3-6).

The Mintzberg et al. model does not discuss which industrial network characteristics are used to inform decisions (the sense making processes in 'mental models') or how the process from stimuli to action unfolds (the relationship between strategic action and the external environment). Several authors have developed different descriptive theories on how decisions are taken within organisations, most notably: 1) bounded rationality, 2) politics and power and the 3) "garbage can" model. Bounded rationality proposes that organisations are constrained by limitations in information and calculation, that their perceptions of the environment are biased and that organisational decisions are affected by internal conflicts (Cyert and March 1963:215). The "politics and conflicts" approach expands on these ideas and describes the process of decision making through imbalance between different interest groups, personal preferences and political games (Eisenhardt and Zbaracki 1992:23). The "garbage can" model describes the decisions as an accidental meeting of choices, problems and participants (Cohen, March et al. 1972:3-4).

To model the decision making process of organisations, this thesis adopts the perspective that organisations can be represented as a single decision unit. From this perspective, it can be argued that bounded rationality is the predominant theory that describes the decision process most appropriate. Although such a perspective has received considerable critique, there are several arguments in favour of adopting a simplified perspective of organisational decision making in the context of this thesis. Firstly, the view that an organisation acts as a single decision maker can represent the

decision making process in a management board room. There is particular information and alternative courses of action presented at the beginning of the meeting and depending on the decision rules applied, a strategic action is proposed at the end. This applies to both purely economic decisions as well as decisions that involve social or environmental consequences. Furthermore, individuals within organisations develop shared norms, values and assumptions that govern how organisations function (Schein 1996:229). Thirdly, the regulatory, normative and cognitive institutions affecting decision making in organisations apply to the organisation as a whole as well as to the individuals within the organisation (Hoffman 1999).

Figure 3-7 shows a simplified diagram of Mintzberg et al.'s model and its position within the analytical framework developed in chapter 2. Furthermore, it shows how the course of action is affected by the functional environment, and by implicit characteristics on an organisational, relational and network level. Although the decision making process is represented as a chronological sequence from "recognition" to course of action, it is not intended to suggest that all decision making processes follow through all the stages. For example, the use of routines can be represented in this model by a particular action that is taken on the basis of a particular stimulus. For example, a new technology with a low payback time becomes available on the market and without considering any other alternatives the organisation decides to buy and install this new technology. In such case, the "development" stage or the "selection" stage do not feature. Thus, although the representation of the decision making process of organisations in an industrial network is represented as four stages, the model can accommodate those processes that do not (necessarily) "follow a formal decision making process".

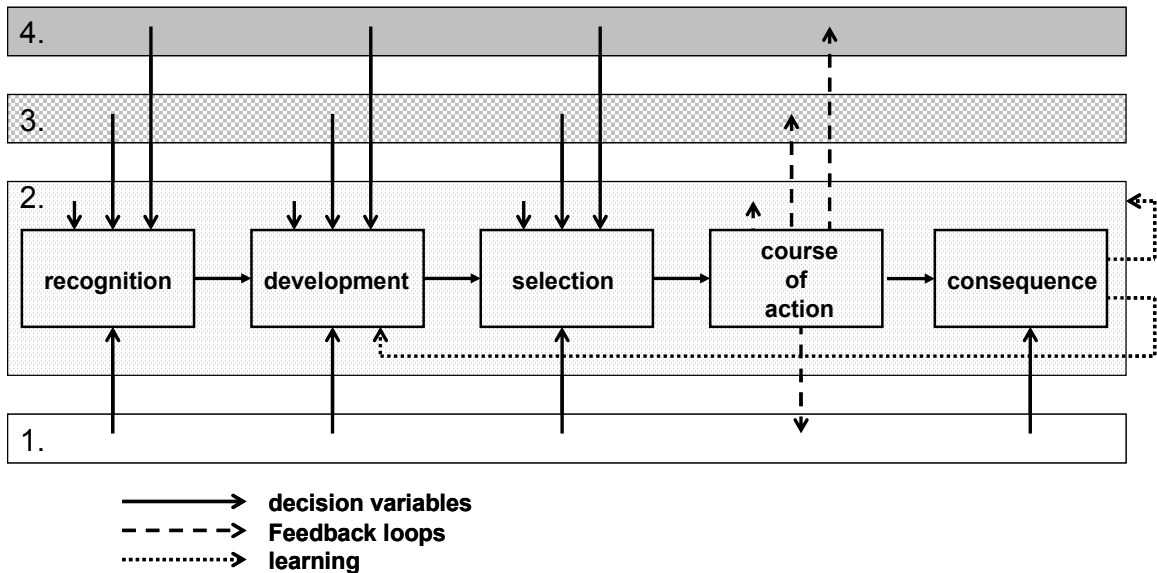


Figure 3- 7 The effect of functional and implicit characteristics on the decision making process of organisations, and the effects of feedback between organisations and their environment

The decision process is simplified to three stages; “recognition”, “development” and “selection”. In the “recognition” phase, an organisation identifies particular stimuli that trigger the need for strategic decisions. These stimuli can be exogenous, or problems or opportunities that occur or arise within the organisation, or within the network (Moss 1981); or they can be developed intentionally through periodical evaluation of the organisation’s position within its environment (Moncrieff 1999). For example, an organisation can respond to external pressures for more environmental friendly practices because of new regulation (an external stimuli), because of a strategic objective to become more environmentally friendly (an internal stimuli) or because competitors have installed the new technology (screening of their position within the environment). The recognition of stimuli can be informed by both functional and implicit characteristics of the organisation or its environment. An example of a functional characteristic that can trigger strategic behaviour is the availability of a new technology, while a shift in interests or perceptions is an organisational implicit characteristic that could trigger strategic behaviour.

On the basis of these stimuli, organisations develop alternative courses of action to respond to the stimuli. This stage is often referred to as strategy formation (Mintzberg 1978; Mintzberg and Lampel 1999). Sometimes the responses to stimuli are

straightforward, in other cases less so. For the latter situations, organisations use implicit characteristics as 'guidelines' or 'rigidities' (Hodgson 1988) to make sense of their environment and react upon the information they receive.

The next stage is the selection process of the appropriate course of action, which is often a choice between action and no-action, and which is a function of the subjective and shared values of the decision makers (Schein 1996:232). Several models are available which describe how decision makers, either explicitly or implicitly, deal with data, values and criteria in their final decision (see for example Tversky and Kahneman 1981; Howard 1988; Gigerenzer and Goldstein 2000; Belton and Stewart 2002).

Consequently, feedback loops exist between the course of action and the functional and implicit characteristics of the organisation, or those of its relationships or network as a whole. In figure 3.6., this is shown by the various connections between the decision making process in level 2, and the other levels. For example, the choice for a particular partner changes the resource streams in the network (level 1), but also affects the implicit characteristics of their relationship, such as past experience and loyalty (level 3).

The last stage is the learning process that occurs after each decision process. The organisation becomes aware of the consequences of its action and can compare this with its initial intent. If the consequences are positive, the strategy formation in the development phase is reinforced (single-loop learning) or the norms and values used to recognise stimuli or develop and select actions are reinforced (double-loop learning) (Argyris and Schon 1978; Smith 2001). In case of negative outcomes, strategy formation or norms and values can be altered in an attempt to achieve better outcomes in the next decision process. However, "defensive routines" can get in the way of double-loop learning (Hannan and Freeman 1984:151). Furthermore, learning does not necessarily lead to more successful decision making processes. The number of occasions to learn is mostly limited, interpretation is affected by historical framings, the criteria for success are often ambiguous and superstition affects the learning process (Levitt and March 1988:323-326).

According to Sterman (2000), both single and double-loop learning can be thought of as changing the mental models of the decision makers. As a consequence of the changed

mental models, the same information now yields a different decision (Sterman 2000:18). The implicit characteristics and processes can be adjusted through learning. This will be discussed in the next section.

In conclusion, the first requisite scale of modelling is the strategic decision making process of organisations. In this thesis, this process is presented as a three stage process, whereby stimuli are recognised, alternative courses of action are proposed or developed and a final decision determines the final action. The characteristics and rules that inform the decision making process are contained within the mental model of the organisation. This mental model can be updated or changed depending on the learning processes that organisations adopt. The next section will discuss in more detail how the next scale of the model, the mental models, can be encoded into an agent-based model.

3.6.2 Interpreting the mental model of organisations.

This section presents a generic framework to operationalise the processes that play a role in the 'mental models' of organisations. The important role of 'mental models' in industrial network evolutions has been highlighted throughout this thesis and this section will discuss how the different 'sense making' processes and 'decision making' processes can be operationalised within a computational model. The focus of this section is not on the different parameters that impact on an organisations decision making process, but on the different processes that take place within 'mental models' and how these processes affect the eventual decision outcome. Namely, in reality, there are an unlimited number of parameters that can affect decision making. For example, every organisation can have slightly different norms and values affecting their decision making process. This section will not discuss how specific norms and values can be parameterised, but will present two mathematical models that can be used to encode the process by which organisations decide what functional and implicit organisational characteristics impact their decision making process and how these functional and implicit characteristics affect the decision outcome. Particular attention will be given to the 'sense making' processes that determine the implicit behavioural and implicit relational characteristics that can affect the decisions of organisations.

Section 3.2.3 discussed the use of agent scenarios in which each scenario represents a different 'mental model', which reflect a different perspective on how organisations deal

with ambiguity. These different mental models are different combinations of functional and/or implicit characteristics and processes of 'sense making' and 'decision making'. A generic overview of the different functional and implicit characteristics is provided within this section, however, in case of modelling a specific mental model as an agent scenario, the modeller can choose to use one or more of these characteristics and processes depending on his/her interest.

The mental model of an organisation consists of information and processes that inform the strategic decision making process. According to Sterman (2001), the mental model of an organisation includes its "beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model (which variables are included and which are excluded) and the time horizon it considers relevant – the framing or articulation of the problem" (Sterman 2000:16). In other words, mental models are "small-scale model(s) of an external reality" required to explain and understand the complex reality in which organisations operate (Craik 1943 in Burns 2000:3). Mental models affect strategic decision making in two ways (see section 2.4): a) mental models provide interpretation of information that informs the decision and b) mental models provide the strategy, structure and decision rules that are used to translate information into action. Figure 3-8 shows how a descriptive model of how the two different processes in mental models (interpretation of information and cognitive decision processes) affect the decision making process within the context of an ever changing external environment (Sterman 2000:19). Loop (A) shows the interpretation of information and loop (B) shows how mental models inform the decision by providing different strategies, structures and decision rules.

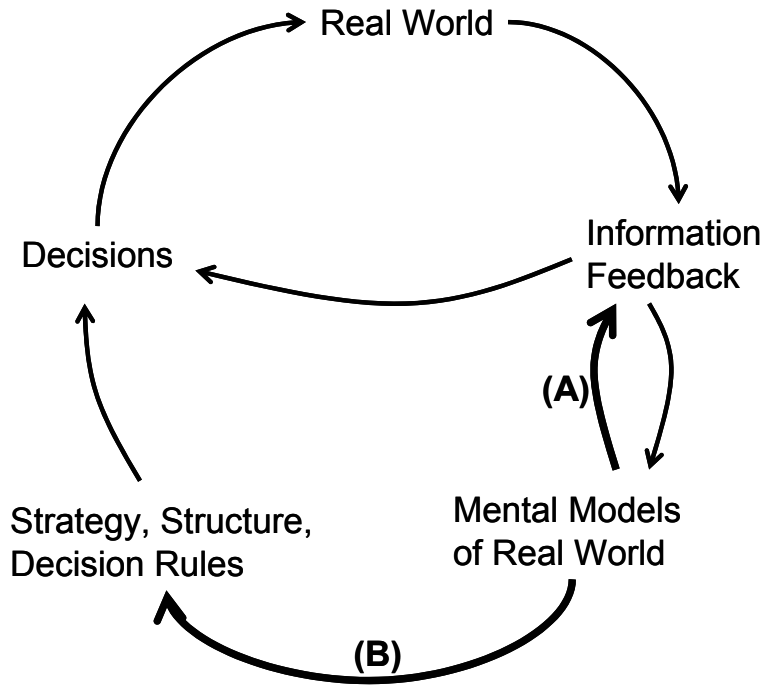


Figure 3- 8 Double-loop learning through information feedback and through a change in mental models (Sterman 2000:19)

The process of interpreting information (loop A) in order to make a decision is known as judgement (Connolly, Arkes et al. 2000:1). On the other hand, the process of converting information into action by using a set of rules characterises a decision process (Forrester 1961:93). In the research area of judgement and decision making, decision analysis is used to decompose a decision process before it takes place, while judgement analysis is used to decompose the process after the judgement has been made. However, instead of using decision and judgement analysis to analyse decisions of individuals, the methodologies can also be used to describe organisational decision making processes. Moreover, both decision and judgement analysis use mathematical models based on simple algebra to represent the process of interpreting information and converting information into action. These two mathematical models are known as a 'decision tree' and a 'Lens model', respectively (Connolly, Arkes et al. 2000:4) Figure 3-9 shows both models.

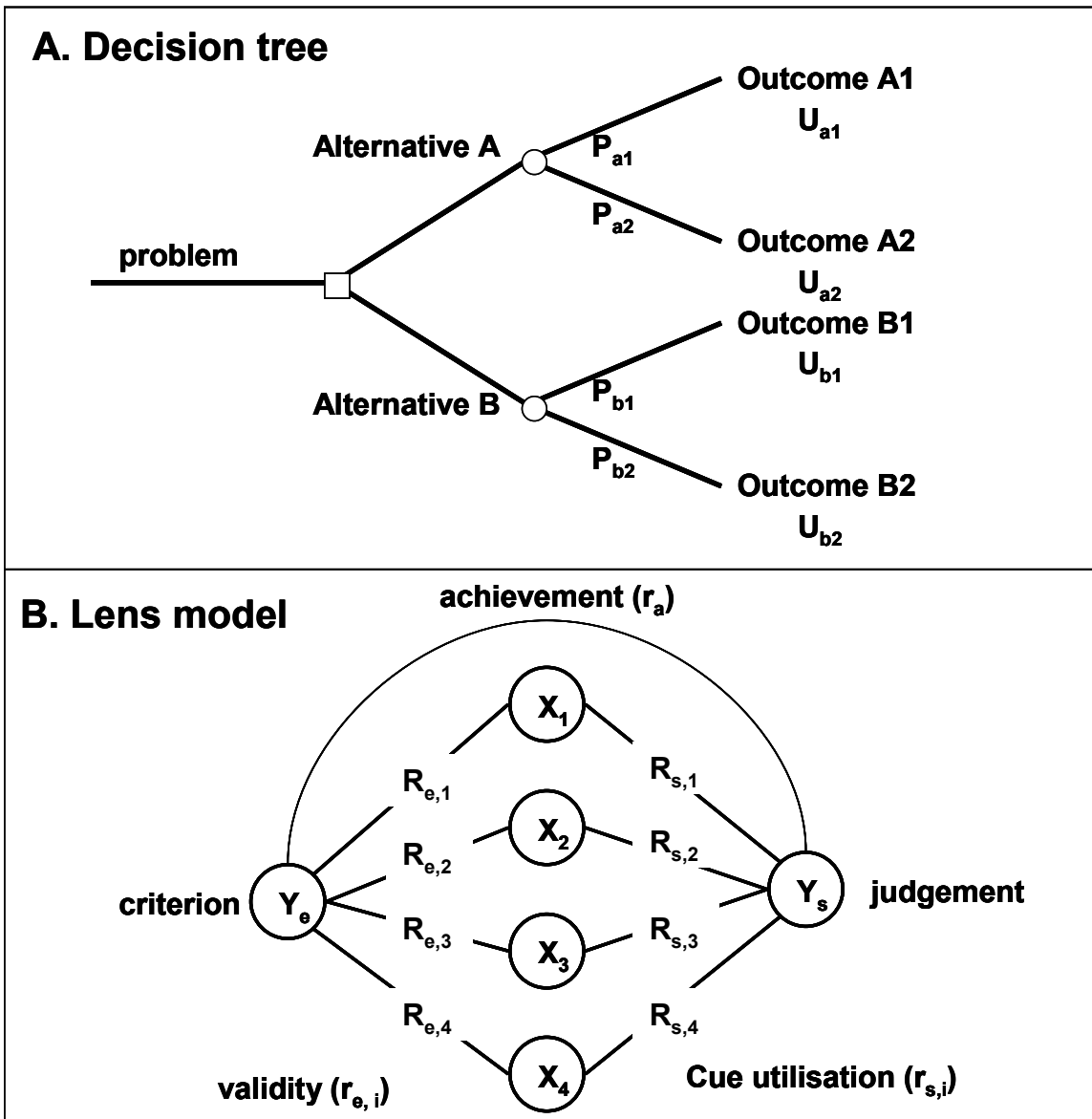


Figure 3- 9 Two mathematical models to represent the decision process and a judgement process (Connolly, Arkes et al. 2000:6-7)

Both models can be used as the basis for encoding the 'sense making' and 'decision making' process of mental models into a simulation model. In the decision tree, the little box represents a decision node indicating possible courses of actions that can be taken by an organisation. The small circles represent chance nodes, indicating that there are several consequences possible from a particular action. In an ideal situation, an organisation has information about all the alternatives possible and their potential consequences, so that it would be able to make a rational decision depending on its

preferences. However, in industrial networks both kinds of information are often unavailable. A decision tree therefore always involves value judgements, a central theme of Multi-Criteria Decision Analysis (von Winterfeldt and Edwards 1986; Keeney and Raiffa 1996; Belton and Stewart 2002). Thus, organisations always use, in one way or another, simplification strategies to determine the number of possible actions and their associated consequences. These simplification strategies can consist of a number of assumptions, or they can consist of simplification strategies that limit the number of alternatives or reduce the number of decision criteria. The choice for a particular simplification strategy determines the outcome of the decision making process. In other words, it is the 'mental model' that determines what information and what decision making processes are used in the strategic decision making process of organisations (as described in section 3.6.1).

The 'Lens model' represents how a person or an organisation draws a conclusion (Y_s) about something (Y_e) without being able to directly observe Y_e . In the case of strategic decision making, Y_e could be the consequences of taking a particular action. However, in order to make a decision a person or organisation will have to use tangible information, also called cues, to infer what Y_e might be. For example, in strategic decisions about investments, cues can consist of historical figures about market growth that suggest a similar growth in the future, or cues could be consumer surveys suggesting that product A is more wanted than product B. The validity of these cues is represented by R_e , and the individual preference of the organisation is represented by R_s . In judgement analysis, this model is used in experimental settings to determine how well the subject's judgement corresponds to the actual criterion value. However, in the case of representing judgements of organisations the same model can be used to describe an organisations' perceptions or beliefs on what is important (ie the validity of their cues) and to describe their preferences (ie how much weight do they assign to each of these cues). Subsequently, the outcome of these judgements can feed into the different decision making models that they use. Judgements on what alternatives are available determine the decision nodes in the decision tree, while judgements on the potential consequences of each alternative determine the chance nodes. Finally, the decision tree can be used to reflect norms, values and 'satisficing' behaviour of an organisation through assigning weightings to the different criteria. The use of decision trees and the

'Lens model' to represent different mental models (in other words, different combinations of parameters and judgement and decision processes) is illustrated in chapter 7.

Together, these two models can represent a large range of different 'mental models' that organisations use to make decisions. For example, bounded rationality can be represented by using the 'Lens model' to determine the number of cues that are used in the decision making process. Similarly, the 'decision tree' model can be used to represent routines as the cognitive processes that determine the possible investments in and consequences of new technologies as suggested by Nelson & Winter (1982). Each routine can be modelled as a process whereby one or more cues are directly coupled to a judgement about which alternative to pursue. Subsequently, the decision making process converts this judgement into action without considering any other alternatives. Similarly, 'satisficing' behaviour can be modelled as a process whereby an organisation uses some strong cues to determine the most obvious action to undertake. If the consequences of this action are perceived to achieve particular threshold criteria, the organisation will execute that particular alternative. If the action does not meet the criteria, the organisation uses judgement to determine the next most obvious action. On the other end of the spectrum, these two models can model a decision making process whereby an organisation explicitly engages with risk and preferences by using different differential weightings (R_e) and function forms (R_s) for the different cues used in the decision making process.

Finally, the decision tree, and especially the 'Lens model', can be used to represent learning. Most theories on learning focus on recurring situations (see box 3.2.), whereby the individual or organisation can use the consequences of its actions to adapt its strategy decision (either through changing its norms and values or by changing the set of alternative actions) (Argyris and Schon 1978). However, most strategic decisions only occur once and there is no generic logic or theory for individuals or organisations learning from history (March, Sproull et al. 1991:10).

Besides individual learning, organisations learn from each other (also referred to as thoughtless learning (Epstein 2001:9)). Especially, in one-off decisions or decision situations that occur infrequently and are surrounded by high levels of uncertainty, learning occurs through two other processes. First of all, interacting agents develop

Box 3.2 Theories for organisational learning

There are many theories on organisational learning. Some theories describe learning as a trial-and-error process (Arthur 1991), as a choice between exploration and exploitation (March 1991), as routine-based, history-dependent and target-oriented (Levitt and March 1988) or as a mechanisms for simplification or specialisation (Levinthal and March 1993). In computational models, genetic algorithms are often used to display learning. Genetic algorithms are developed by Arthur (1991) and mimic the learning process of organisations by trial-and-error (Arthur 1991:354). However, trial-and-error learning can only take place in situations where an organisation has to make iterative choices between a constant set of alternatives with unknown consequences. Only in those situations, can an organisation learn from the consequences and update its information about the alternative.

Several other processes have been identified that govern the way in which organisations adapt their norms, policies and objectives. Levinthal and March, for example, identified two important mechanisms that facilitate learning from experience: simplification and specialisation. Simplification seeks to simplify experience, to minimize interactions and restrict effects to the spatial and temporal neighbourhood of actions. Specialisation, on the other hand, tend to focus attention and narrow competence. When an organisation is successful, it decreases the intensity of search for alternative solutions, it increases the level of organisational flexibility and the targets (aspiration levels) for performance. (Levinthal and March 1993:96-100).

Although these theories are useful descriptions of learning processes and might be explored within an agent-based modelling framework, they are not explored within the context of this thesis. The main reason is that strategic decisions rarely take place under the same circumstances with the same alternatives available. Instead, most strategic decision situations are unique and experience is not available under such circumstances.

mutual awareness, or 'shared understanding', about the environment in which they operate, which manifests itself in regulatory, normative and cognitive institutions (DiMaggio and Powell 1983:147). These processes are modelled on the scale of social embeddedness (see section 3.6.4). However, the learning process in the 'mental model' takes place if an organisation adopts these norms and values as informational cues in the decision making process. This process of learning can be modelled by allowing new cues to become part of a judgement or by strengthening or weakening the validity of a particular cue. Secondly, organisations can learn by the process of interorganisational

imitation (Haunschild and Miner 1997). While learning through social institutions affects the norms and values that inform decisions, learning through imitation affects the alternatives that are considered, such as the range of technological options that are considered, which can be represented as changes in the decision nodes.

It is important to stress that the 'mental model', as it is modelled within the agent-based modelling framework, represents a set of processes rather than a particular set of functional and/or implicit characteristics. The particular choice of which processes are used to extract information and/or make decisions reflect the organisations perception towards the inherent uncertainty it faces within an ever changing environment. This includes the learning process that an organisation adopts. The 'mental model' is a separate scale within the multi-scale model of industrial network evolution, because these judgement, decision and learning processes have their own dynamics (for example, decision processes take place every year), which are different from the dynamics of the functional network in which they operate (which changes monthly in the case study) or the dynamics that represent the social embeddedness of organisations and the emergence and/or breakdown of social norms and values (which has a much longer cycle than the decision making processes of individual organisations).

In conclusion, this section argues that the mental models of organisations can be encoded as two processes. The first process uses cues to make judgements about potential alternatives / actions that could be undertaken, and the potential consequences associated with these alternatives. The second process uses this information to decide upon a particular action. By combining these two processes, a large range of different mental models can be encoded into a simulation model.

3.6.2.1 Modelling processes determining relational implicit characteristics

Section 2.5 provided an overview of the different implicit relational characteristics that affect the decision making of organisations. The next section discusses, in much more detail, how these theories can be encoded in a model. Particular attention will be given to two of the most important characteristics that affect the choice between potential partners: trust and loyalty. On the basis of literature on trust and loyalty, the concepts will be decomposed into elements that can be specified in more detail. Subsequently, a generic framework is presented that describes the processes by which an organisation

might determine to trust or show loyalty towards other organisations. Obviously, the values and parameters used within the process can be adjusted (or excluded) to reflect 'mental models' whereby an organisation does not use 'trust' and/or 'loyalty' to inform its decision making process.

3.6.2.1.1 Trust in relationships

Much research has been done in the field of interorganisational relationships to understand why and how relationships are established or terminated, and the effect of existing relationships on the behaviour of agents involved (see for example Raiffa 1982; Granovetter 1985; Eisenhardt 1989; Podolny 1994; Ring and Van De Ven 1994; Haunschild and Miner 1997; Uzzi 1997). However, only a few scholars have tried to quantify the concept of "trust" into computational models; and these attempts have been fairly rudimentary with trust modelled as a scalar on a nominal scale independent of system performance and evolution (see for example Nootboom, Klos et al. 2001:89; Perrons, Richards et al. 2005).

Trust is a very elusive concept. According to the German philosopher Luhmann, trust should be understood specifically in relation to risk. Trust presupposes the awareness of an individual organisation of risk; the organisation recognises the different alternatives and considers the encountered risk (Luhmann 1984:25). Uzzi (1997) elaborates on this relationship between trust and risk by stating that trust is more closely aligned to heuristic-based processing than to identifying a predilection for risk-based behaviour (p. 43). Similarly, Ring and Van De Ven (1994) propose that trust can be decomposed into two characteristics: 1) a risk perspective based on confidence in the predictability of one's expectations and 2) a view based on confidence in another's goodwill and trust as a level of 'fairness' within a relationship (p. 93).

The risk perspective of an organisation about other organisations can be decomposed into three characteristics. Firstly, the risk perspective is related to the risk profile of an organisation; the production methods used, the insurance mechanisms in place and the quality of the product and/or resource. This is a functional characteristic of an organisation. Secondly, the risk perspective is determined by past experience. Podolny (1994) found that if uncertainty is high, organisations will engage preferentially with those organisations with whom they have transacted in the past (p. 459). He also found that if market uncertainty is high the probability increases that organisations engage in

transaction with those of similar status (p. 461). Status has two structural components: the size of the organisation and the number of connections an organisation has. The size of the organisation is used as an approximation for how successful an organisation is and can be measured in terms of production volume, turnover or number of employees depending on the industrial network (Haunschild and Miner 1997:476). The number of connections an organisation has does not only provide an indication of conveying resources between organisations, but the presence (or absence) of connections also provides information about the underlying quality of that organisation (Podolny 2001:35). In conclusion, the risk perspective related to trust can be decomposed into the risk profile of a potential partner, past experience and status, whereby status can be decomposed into the size of the organisation and the number of connections an organisation has.

The second characteristic of trust is a perspective of the level of 'fairness' within a relationship. The level of fairness can be seen as a determinant of relationship quality (Kumar, Scheer et al. 1995:54) and operates as a lower-bound constraint on choosing the appropriate partner. It operates as a heuristic characteristic that permits organisations to be responsive to stimuli and to speed up decision making (Uzzi 1997:42). Further, Kumar, Scheer et al. (1995) suggest that reliability and benevolence are two key factors that determine the perception of fairness within a relationship. An organisation is perceived as reliable when it continuously satisfies the agreed conditions about deliveries of material and information and when it is knowledgeable about its business. Benevolence is perceived willingness of the other organisation to act in a way that benefits the interests of both parties. These implicit characteristics of organisations have both a strong positive effect, directly and indirectly, on the degree of fairness between two organisations (Selnes and Gonhaug 2000:265).

These characteristics identified in this literature review coincide with qualitative studies that have been trying to analyse how trust affects organisations' decision making. Recently, Hurley (2006) conducted a qualitative analysis to develop a predictive model for analysing the effects of trust. Hurley categorises the determinants into "decision-maker-related" characteristics and "decision-situation-related" characteristics. Depending on whether an organisation would assign a high or a low score to the different characteristics, Hurley tried to predict whether the organisations would establish

a relationship. Although Hurley uses more fine-grained characteristics (ie 'good communication' and 'integrity'), his characteristics all fit into the same categories of characteristics used in this thesis.

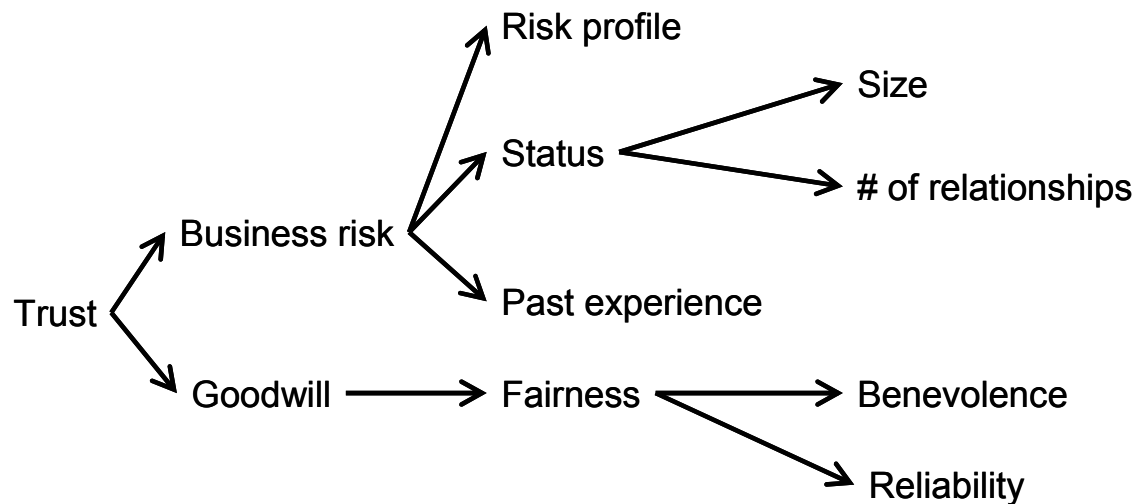


Figure 3- 10 Attributes of trust

Figure 3-10 provides an overview of the characteristics that have been identified to inform trust. The decomposition of trust into measurable and quantifiable characteristics allows trust to be encoded into an agent-based model, and used to explore the effects of these characteristics on the decisions of organisations, and on the evolution of the industrial network as a whole. Although the exact relationship between trust and the functional and implicit characteristics is unknown and depends on the mental model that is used by the organisation under consideration, the model allows for explicit exploration of different assumptions about these mental models and how they affect the evolution of industrial networks. A methodology to select a range of mental models to explore industrial network evolution is discussed in chapter 5.

3.6.2.1.2 Loyalty in relationships

Maintaining relationships is an important aspect of organisational success. From a resource-based perspective, relationships are important to gain access to scarce resources or to secure a position within an industrial network (Eisenhardt and Schoonhoven 1996; Lavie 2006). Continued relationships are, however, not only important from an economic point of view (Dyer and Singh 1998:664), but also from a social-psychological perspective (Ring and Van De Ven 1994:1004; Narayandas 2005:132). Examples of such non-tangible non-financial benefits are going beyond the

letter of contract, thinking ahead in terms of customer's needs or delivering on holidays to keep a customer's production lines going (Narayandas 2005:134). These relationships, especially over longer period of times, transform from economic exchange relationships into socially embedded relationships involving trust, fine-grained information transfer, and joint problem-solving arrangements. They contribute significantly to the success of the individual organisations involved (Uzzi 1997:42). Such developments bind organisations together, especially in circumstances whereby organisations experience high levels of market uncertainty (Beckman, Haunschild et al. 2004:272).

Selnes and Gonhaug (2000) found that reliability and benevolence are two attributes that not only affect the level of 'fairness' between two organisations (see paragraph 3.6.2.2), but also increase the loyalty between two partners through increased satisfaction and positive effect (p. 259). Both of these attributes are required to explain loyal behaviour. Reliability makes organisation to be more inclined to be loyal towards organisations that satisfy demands. However, satisfaction alone is not sufficient to explain loyal behaviour (Narayandas 2005:136). An organisation has to be benevolent as well, and provide services beyond those required. The third characteristic that affects loyalty is the duration of a relationship. Ring and Van de Ven (1994) found that, as the temporal duration of the relationship between two organisations increases, the likelihood decreases that the organisations will terminate their relationships when a breach of commitment (the fourth characteristic) occurs (p. 107). The reason for this behaviour is that past experience provides a great deal of information about the other organisation, while the search for new partners will confront an organisation with an uncertain situation.

These four characteristics suggest a possible decomposition of loyalty into narrowly defined elements, which subsequently can be conceptualised and quantified in the context of an industrial network analysis. Figure 3-11 shows the relationships between the four characteristics and loyalty.

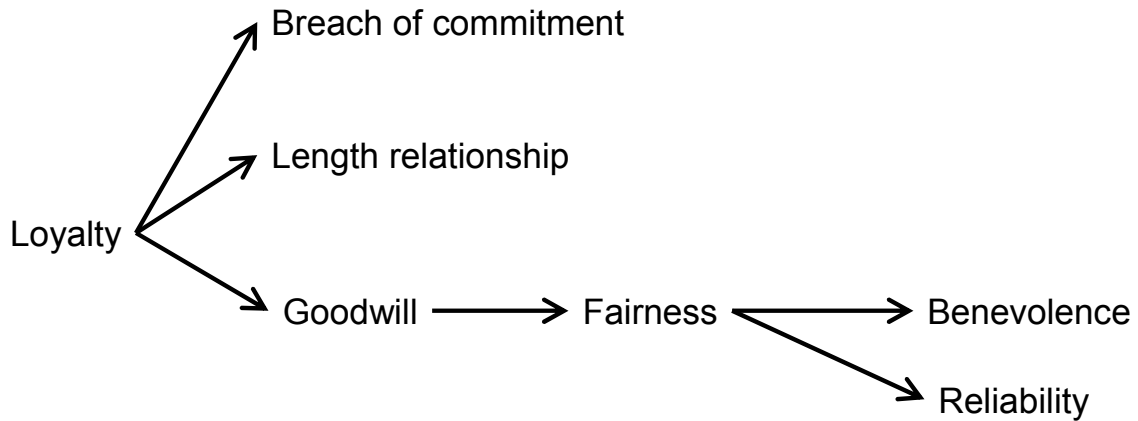


Figure 3- 11 Attributes of loyalty

3.6.2.1.3 Modelling trust and loyalty

Modelling the different functional and implicit characteristics that determine the level of trust and loyalty between organisations requires a quantitative approach to evaluate the various characteristics simultaneously in a comparable manner. Section 3.6.2. discussed how the mathematical models of judgement and decision models can be used to model how 'mental models' inform the decision making process. It is suggested here that techniques from multi-criteria decision analysis (MCDA) provide appropriate tools to asses the effects of multiple, diverse characteristics of different scales simultaneously. Furthermore, MCDA has developed techniques to model different compensatory and non-compensatory decision procedures, which can reflect different processes by which organisations use threshold values to convert information into action (von Winterfeldt and Edwards 1986; Keeney and Raiffa 1996; Belton and Stewart 2002). Finally, MCDA techniques can explicitly consider value or utility functions, which represent the different perspectives and attitudes of the decision maker; in this case the organisation.

Box 3.3 Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) has been developed to aid decision makers that are faced with difficult problems characterised by complexity, uncertainty, multiple objectives and the need to consider different perspectives. MCDA provides a set of analytical frameworks that systematically reveal the trade-offs available, the uncertainties involved and the underlying preferences of the decision makers (von Winterfeldt and Edwards 1986).

The multi-criteria frameworks developed within MCDA are efficient tools to represent the perspectives of a particular decision maker, whereby the decision makers ethical principles, goals and aspirations, informational cues and simplifications, and norms and values can be translated into a model using objectives, criteria, attributes and values judgements. Objectives, criteria and value judgements can be expressed as qualitative statements or quantitative expressions, and on different scales, depending on the characteristics of the decision problem. MCDA has mainly been used as a normative tool helping organisations to make better decisions. However, the techniques that are used in MCDA can also be used descriptively. The decision objectives capture the reasons for interest in the decision, criteria can reflect the norms and values an organisation holds, and decision attributes (or assessment indicators), when normalised, represent cues and value judgements consistent with the preferences of the decision maker.

Several techniques have been developed throughout the history of MCDA for considering conflicting objectives and uncertainty. Initially, methods were developed to consider multiple objectives in the development of 'optimal strategies' to maximise utility. Then, these methods were expanded with consideration of multiple objectives and value functions in Multi Attribute Utility Theory, permitting trade-offs between different dimensions. Subsequently, MAUT was expanded considering a range of alternative approaches to consideration of multiple objectives, under both conditions of certainty and uncertainty, and became known generally as MCDA. Finally, MCDA was extended from the limited 'mechanical-unitary' context to 'ill-structured problems' that require engaging with multiple stakeholders, greater emphasis on 'structuring' and engaging with conflicting objectives (Basson 2004:2-15).

Box 3.3 Multi-Criteria Decision Analysis (continued)

However, there are still limitations to the use of MCDA:

- assumes a commitment to a deliberative and consensual process
- assumes all stakeholders are willing to participate
- denies social complexity
 - o ignores power
 - o ignores differences in information, knowledge and empowerment
 - o assumes world views can be changed
- tends to place emphasis on aspects that are amenable to quantification (Jackson 1991).

This thesis uses MCDA techniques in three ways. Firstly, MCDA tools are used to assist in the uptake of decision making processes within simulation models. In chapter 4, MCDA techniques are used to consider conflicting objectives in the evaluation of sustainable development and in chapter 5 MCDA techniques are used as a normative basis for evaluating interventions to stimulate sustainable development in industrial networks.

The following methodology has been followed. Following the identification of appropriate proxy indicators for trust and loyalty, based on the logic of Table 3-3 below, for each of these attributes a local range from “worst” to “best” performance is determined. The range is local, because each organisation can have different worst and best performances for a particular characteristic depending on its current situation and the potential partners available. The “worst” performance is assigned a value of 0 and the “best” performance is assigned a value of 1.

Table 3- 3 Characteristics (or cues) that are used to determine the level of trust and loyalty

Characteristic	Quantification method	Quantification of range
<u>Size:</u>	Depending on the network, the size of organisation can be determined by: <ul style="list-style-type: none"> - the amount of resource under control of the organisation - the capacity - the amount of output 	The range is determined by the lowest and highest value of organisations operating in the network
<u>Connections</u>	The number of relationships is defined by the number of existing contracts with any other organisation at a particular point in time.	The range is determined by the total number of organisations (minus one) that are available at the time of the decision.
<u>Past experience:</u>	The number of previous contracts between two organisations. This attribute is relationship-specific.	The range is determined by the potential amount of contracts that could have been established at the time of the decision given the current contract length.

<u>Reliability:</u>	Reliability can be related to the frequency of non-compliance throughout the year.	The range is determined by the largest number of times any partner has breached contract-commitments
<u>Benevolence:</u>	Benevolence is measured in terms of the number of times that no negotiation over price was required in order to establish contracts between two partners. This attribute is relationship-specific.	The range is determined by the total number of contracts established between the two specific partners.
<u>Length relationship:</u>	The length of the relationships is measured in the number of consecutive contracts between two partners. This attribute is relationship-specific.	The range is determined by the maximum number of contracts that two partners potentially could have had at a particular point in time.
<u>Conflict:</u>	Conflicts are measured in terms of the number of times that a negotiation took place, but no agreement was met to set up a contract. This attribute is relationship-specific.	The range is determined by the total number of times that the two agents have been in touch with each other.

Subsequently, a value function is used to provide information relating to the intra-criterion preference relationship for a particular characteristic within its scale. Different value functions for each of the characteristics can be used to reflect different values and preferences of the organisation, ie different mental models. The next step is to assign particular weightings to each of the characteristics (i.e. inter-criterion preference relationships), whereby the total sum of weightings is equal to 1. Depending on the weighting, an overall score for trust and loyalty is determined, which ranges between 0 and 1 and which is specific for each of the potential partners. The final outcome of this process is a ranking of the trustworthiness and loyalty of potential partners.

The final stage is representing the role of trust and loyalty in the decision making process of an organisation. It is argued that trust acts as a pre-screening process in the choice for partners, while loyalty has a compensatory role. Figure 3-12 represents the decision making process of choosing between potential partners and the role of trust and loyalty within this process.

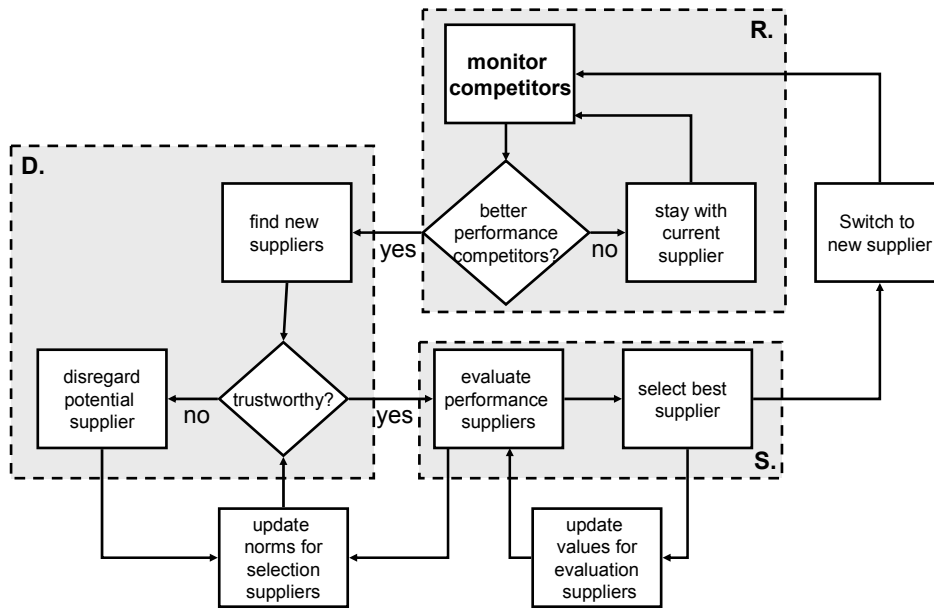


Figure 3- 12 The role of trust and loyalty in choosing partners

Figure 3-12 provides a logic diagram for the process of choosing a new partner within the modelling framework for strategic decision making. The reason for finding new partners is developed in the recognition stage (R), potential partners are screened in the development stage (D) and a choice is made in the selection stage (S).

As proposed by Uzzi (1997), trust can be seen as a lower-band constraint on choosing the appropriate partner. Following this perspective, there is a threshold value under which the level of trust between potential partners is not sufficient to pursue any further exchange of information. Trust, as such, acts as a screening mechanism whereby those potential partners whose trustworthiness is above the threshold are pursued further, while the other partners are disregarded without contacting those organisations for further information. Such process reflects the findings of psychological and organisational research on decision making, where it is argued that a large number of potential partners would increase the transaction costs associated with a detailed evaluation of each alternative; and secondly, the cognitive limitations of decision making bound the number of alternatives that can be evaluated simultaneously. The mechanism

of pre-screening becomes more important if the number of alternatives (or in this case potential partners) is large.

The threshold value itself is situation dependent. The threshold cannot be modelled as a specific value that represents the turning point from trustworthy to untrustworthy (figure 3-13a), because

- 1) the trustworthiness of potential partners is different at any point in time and
- 2) the value of trustworthiness for a particular partner depends on the trustworthiness of other potential partners.

Instead, threshold values are expressed as a function of the distribution of trust values within the specific decision context. As previously mentioned, economic and social sciences indicate that this threshold is often placed such that the organisation is left with a small number (typically three or four) potential partners to choose from (see figure b). The threshold value, thus, can be expressed as the top 3 or 4 potential partners or as a percentage of the total population.

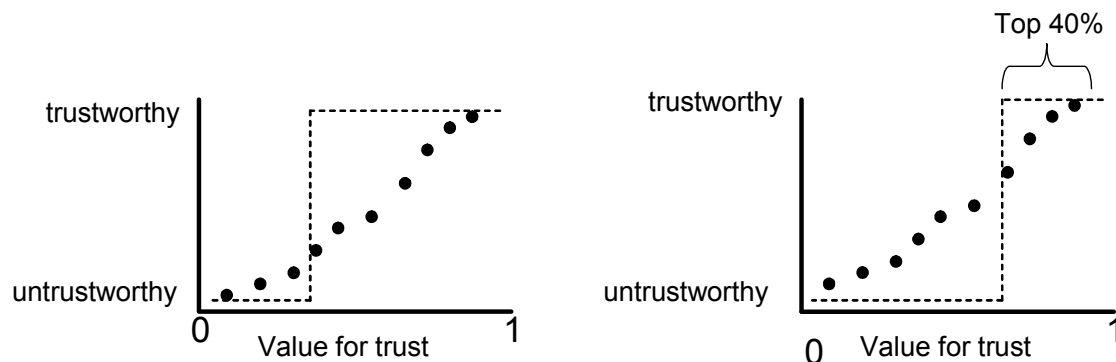


Figure 3- 13 Identifying the trustworthy partners on the basis of a threshold. A) represents a static threshold value, while B) represents a threshold value that takes the context into consideration

Loyalty, on the other hand, affects the decision making process differently. After an organisation has selected a number of potential partners, their characteristics (ie price and quantity) have to be evaluated. In this evaluation process, the level of loyalty is of a compensatory nature. If the level of loyalty between two potential partners is low, it can diminish the functional value of that particular partner. On the other hand, if the value is high it can compensate for inferior functional characteristics of a potential partner. For

example, two suppliers can offer to sell the same amount of resource for the same price. However, if the buyer feels more loyal towards on the potential supplier, it will prefer that organisation over the other. Loyalty, in economic transactions, is often expressed as a price premium, which indicates that loyalty can compensate for price differences up to 10%. As is the case for trust, the value of loyalty is context-specific. In a newly established network, two consecutive contracts between two partners can indicate a high level of loyalty, although two consecutive contracts could have limited value in terms of loyalty for long-established networks.

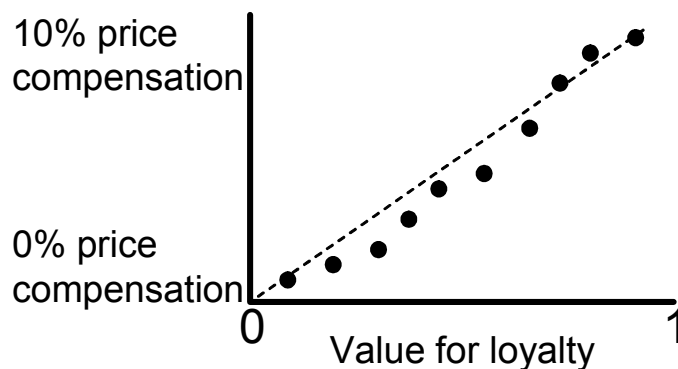


Figure 3- 14 Role of loyalty expressed in price compensation

Figure 3-14 represents a number of different potential partners and their loyalty values on a scale from 0 to 1. Depending on the loyalty between the decision maker and the potential partner, a compensatory value for price differences is determined. For example, the potential partner that the decision maker feels the highest level of loyalty towards, will still be selected if its price is 10% higher than the potential partner that receives no loyalty feelings. Similarly, loyalty can play a role if an organisation decides to set a price for its products. To those potential buyers that are perceived as loyal, the supplier can introduce a discount of up to 10% on the price of its products.

Figure 3-14 illustrated the effects of loyalty on an organisations choice between potential partners on the basis of the economic prices that these organisations offered. However, the same methodology can be employed for organisational choices on the basis of other criteria. For example, an important subject within supply chains is the extent to which suppliers fulfil particular environmental and social performance standards. These standards are sometimes based on national regulation in which the suppliers are

located, but more often are determined by the most important organisation within the supply chain. In such circumstances, the role of loyalty can affect the decision choice on the basis of the environmental or social performance of the potential partners.

In conclusion, trust and loyalty are two implicit relational characteristics that affect the decision making process of organisations when choosing between potential partners. Representing trust and loyalty is important for understanding the evolution of industrial networks, because their effects on the outcome of the decision determine the new structure of the network and therefore the functional characteristics of the system and the social processes that determine network wide institutions. Although trust and loyalty are relational characteristics, they can be modelled as part of the mental model of an organisation, because their dynamics depend on when organisations make decisions.

3.6.3 Modelling processes on a system network level

Modelling the system performance of industrial networks entails three important issues. Firstly, the system performance should entail the emergent properties of the system of interest to the analyst. Secondly, it includes the external factors that impact on the evolution of the industrial network. Thirdly, it determines the timescale and dynamics of the industrial network evolution.

Firstly, the system level represents the system performance criteria that are of interest to the analyst and/or which impact on the decision making processes of the organisations within the network. For example, these system performance criteria can reflect the level of economic activities of a region or the environmental impacts of industrial activities. Furthermore, the system level entails those network characteristics that present the alternatives available to the organisations within the network, such as the technologies available, infrastructural constraints and/or geographical and hydrological information about the region. Finally, in the context of this thesis, it is important that those functional and structural features of the industrial network that determine sustainable development of the system are represented on a systems level (ie the economic, social and environmental impacts of the development of a bioenergy network). These characteristics will be discussed and developed in more detail in chapter 4 and illustrated in the case study description in chapter 6.

The second important issue that should be represented are the external factors that impact on the industrial network evolution, especially if these external impacts are change dynamically over the time. For example, the oil price will have an important impact on the economic viability of biofuels and is likely to change over the course of the analysis (30 years from now). These external parameters and their rate of change need to be modelled on a systems level. In the case of industrial networks, these exogenous variables could also be the outputs of other industrial networks impacting on the evolution of the system, or global markets affecting the prices of resources and products provided by the industrial network. The exogenous variables represented on a systems level can also be used to develop the 'context scenarios' reflecting the analyst's view on potential futures and how they might affect the network evolution. The use of exogenous variables to develop context scenarios is discussed in more detail in chapter 5 and illustrated in the case study in chapter 7.

The third important issue in terms of modelling system performance is the time scale that is used to assess the dynamics of the system as a whole. Depending on how frequently organisations make decisions that affect the function and structure of the industrial network, the modeller has to choose a time scale that reflects the dynamics without being computationally too cumbersome. For example, the case study that is used in this thesis involves bagasse, a by-product of sugarcane, as the main resource entering the network. Since bagasse is harvested monthly and is available in different quantities each month, the system performance has to be modelled on a monthly basis to reflect the dynamics of the network evolution. Chapter 6 discusses the details of the case study in more detail.

3.6.3.1 Innovation processes

The innovation process, as defined as the diffusion process of new technologies within a system, is a function of the decision making processes of organisations within the industrial network. Their decisions to adopt a technology affect the diffusion of these technologies throughout the network.

Besides the important role of organisations in the diffusion of technology, two other processes can be identified that impact on the diffusion of innovation through the network: 'learning by doing' and 'learning by experiment'. The first process consist of

incremental innovations on existing technologies and can be reflected by learning curves (Berglund and Soderholm 2006; Pan and Kohler 2007). Learning curves are commonly expressed on the basis of costs and cumulative capacity (Arrow 1962:160):

$$C_t = C_0 E^{-\alpha} \quad (3-1)$$

where C_t is the unit of cost of technology at time t , C_0 is the initial costs and E is the cumulative production capacity up to time t . The index α reflects learning-by-doing. An α of 20% means that with the doubling of capacity, the costs for the technology will decrease with 20%. Learning curves are often assumed to be exogenous in policy documents that attempt to evaluate the potential of future technologies, but the rate of 'learning by doing' obviously depends on the number of organisations that have implemented these technologies (Raven 2006).

The process of 'learning by experiment' might result in radical innovations. Although there are no formalised methods to model radical innovation, the modelling approach suggested in this thesis allows for analysing the potential effects of radical innovation. In short, radical innovation can be represented as 'black-box' technologies with a particular efficiency and costs and/or other characteristics of importance to the evolution of the system. For example, there might be a radical breakthrough innovation involving cheaper enzymes to process cellulosic materials in bioethanol. The model can be endowed with the characteristics of this breakthrough technology and as the model evolves, organisation might choose to adopt these 'black boxes' depending on the features of the innovation, the risk associated with adopting the innovation, and the infrastructural features of the industrial network at the time of the adoption.

Both processes, the role of 'learning by doing' and 'learning by experiment' will not be explored in the context of this thesis. However, policy makers and/or organisations interested in the potential consequences of these two processes on the effects of their strategic decisions might wish to include these processes into the 'system performance' level of the model.

3.6.4 Modelling social embeddedness.

This section discusses how processes of social embeddedness can be encoded into the model. The application of social embeddedness processes within the bioenergy case network is illustrated in chapter 7. Section 2.6. discussed a number of theories that have proposed mechanisms that describe the development of institutions in an industrial network. This process consists of four stages (DiMaggio and Powell 1983:148):

1. increasing interaction,
2. emergence of sharply defined interorganisational structures of domination and patterns of coalition,
3. increase in the information load,
4. development of mutual awareness.

In section 2.6., it was argued that institutionalisation is an important factor in the development of industrial networks. It creates mutual understanding between organisations, increases the level of trust between the existing organisations and reinforces existing relationships (Granovetter 2005:2). On the other hand, institutions create niches for newcomers to enter the network (Li and Berta 2002:343).

In order to model the process of institutionalisation, it is important to distinguish between the different attributes of institutionalisation and the different processes for its uptake that have been identified in section 2.6. The three attributes of social institutions that are important for industrial network evolution are: routines, norms and domination (Giddens 1984; Barley and Tolbert 1997; Hoffman 1999:351). The different processes are: dependency-based, history-based, frequency-based, outcome-based and trait-based (DiMaggio and Powell 1983; Haunschild and Miner 1997). The heuristics to model institutionalisation are discussed in the table below.

Table 3- 4 A summary of heuristics that can be used to model social embeddedness and institutionalisation

Process	Heuristic
Dependency-based	If two organisations are dependent on each other, they can share norms. If one organisation is completely dependent on the other organisation, the dependent organisation adopts the norm of the other organisations. If both organisations have are independent, norms are shared.
History-based	If two organisations have a shared history that is longer than average, they can share norms. If one organisation is completely dependent on the other

	organisation, the dependent organisation adopts the norm of the other organisations. If both organisations have are independent, norms are shared.
Frequency-based	If an organisation is consistently outperformed by other organisations that are similar, it will adopt those routines that are used most in the network. The choice of routine is informed by the frequency by which each routine is used in the industrial network.
Outcome-based	If an organisation is consistently outperformed by another organisation with the same function, it will imitate the routines of the more successful organisation. Outcome-based imitation requires a process to determine whether the other organisation is more successful. This 'success'-threshold is context specific and depends on the market position of both organisations involved. If both organisation operate in the top-end of the market, then no adopt will take place by the lower-ranked organisation. However, if the adopting organisation is not located in the top 10%, say, it will try to adopt the routines of the more successful organisation.
Trait-based	If an organisation is consistently outperformed by other organisations with the similar function, it will adopt the routines of the organisation with the highest status. Trait-based imitation requires a process to determine whether the other organisation has a higher status. This 'status'-threshold is context specific and depends on the market position of both organisations involved. If both organisation operate in the top-end of the market, then no adopt will take place by the lower-ranked organisation. However, if the adopting organisation is not located in the top 10%, say, it will try to adopt the routines of the organisation with the highest status.

Depending on the attribute and depending on the mental model(s) which organisations employ, different processes will have to be modelled. Norms are institutionalised through social interaction and mutual awareness (involving some kind of negotiation process) and are therefore either dependency-based or trait-based. Routines, on the other hand, can be adopted by other organisations on a one-to-one basis without any interaction or negotiation required. The institutionalisation of routines can therefore be modelled as frequency-based, outcome-based or trait-based depending on the mental models employed. Finally, power is not institutionalised through a process, but power is an institutionalised attribute that reflects the structure of the network. Of course, the structure is indirectly affected through institutionalisation processes of norms and routines.

The heuristics that are presented in this section represent a series of different institutional processes that can take place on a network level in an industrial network. It is important to represent these institutionalisation processes explicitly, because they affect the actions of organisations and determine for a great deal which organisation can enter or are excluded from the network. Furthermore, it is important that the institutionalisation process is modelled on a separate scale, because the dynamics of institutionalisation are different from the processes on a functional or organisational level. Finally, it is important to recognise that not all institutional process take place, but that it depends on the organisations involved, their perspectives about the other organisations and about the way they are able to handle future uncertainties. The analysis of different social embeddedness processes in the evolution of industrial network evolutions, and their relationship to different 'mental models', is discussed in chapter 5 and illustrated in the case study in chapter 7.

3.7 Conclusions

This chapter has addressed the questions of why and how modelling can be used to understand the complex interaction between organisational behaviour and industrial network evolution, and how models can be used to develop interventions to stimulate sustainable development. In section 3.1., it is argued that models of complex adaptive systems can only be used descriptively, because their complexity makes it impossible to predict their outcomes and the autonomy of organisations makes it impossible to optimise the system. Simulations are most appropriate for complex adaptive systems, because they use a combination of inductive and deductive reasoning to identify and explore the processes that drive system evolution. Furthermore, it has been argued in section 3.2 that simulations are most useful for the development of interventions if they are implemented as non-linear system dynamics models. Non-linear system dynamics models are able to model the emergent behaviour of complex systems, while they can also relate particular changes in interventions to changes in the network evolution. While other modelling methodologies, like self-organising or evolutionary models, might be able to mimic real-world processes by introducing distribution functions and random processes, they are not able to systematically interrogate the consequences of interventions to the evolution of complex systems.

Furthermore, it is argued that the complexity represented within a model depends on both the research questions and the industrial network under investigation. Complexity can be represented by developing multi-scale models. Multi-scale models reflect complexity, because they are able to model explicitly how subsystem interaction results in emergent properties on different scales. It is argued that agent-based modelling is a modelling tool that allows the modelling of multi-scale complexity in a flexible and convenient way, which can be most easily augmented with other methodologies to address the complexity of sustainable development. The final section of this chapter has discussed in more detail how a non-linear system dynamics multi-scale model of industrial network evolution can be operationalised into an agent-based model. Examples have been provided for the modelling of the different industrial network characteristics and the processes that drive these changes of these characteristics over time.

The development of different 'mental models' as agent scenarios, and the role of the different judgement, decision, learning and institutional processes, within each of these scenarios is discussed in more detail in chapter 5. The development of the multi-scale model a bioenergy case study is discussed in chapter 6 and the application, including modelling results is discussed in chapter 7.

Sustainable development in industrial networks

4.1 Purpose and scope

The final aim of this thesis is to develop a methodology that can be used to evaluate different interventions and their effect on sustainable development of an industrial network. To this extent, the previous two chapters have discussed how an industrial network can be analysed and how this can be converted into a modelling approach that provides an understanding of the dynamics of the system. The focus of the previous chapters was on the organisations within an industrial network and how their decisions affect the network evolution. The purpose of this chapter is to develop a methodology to evaluate and assess sustainable development of an industrial network. Specifically, this chapter focuses on a methodology that allows for a comparison of different evolutionary pathways for a given industrial network in terms of their contribution to sustainable development. As such, this chapter is written from the perspective of the analyst, who can be one of the organisations within the network, but who is interested in the overall industrial network performance in terms of sustainable development.

If one considers sustainable development of industrial networks, four characteristics can be distinguished:

1. the function of the network is an emergent property of contributions of the individual organisations within the network,
2. the structure of the network is determined by the relationships between the organisations and the infrastructures within the network,

3. the network operates within a larger context which is constantly changing and affecting the function of the industrial network and
4. the strategic decision making processes of organisations within the network constantly change the function and structure of the network.

These four characteristics of industrial networks have important implications for a methodology to evaluate sustainable development of industrial networks. Firstly, the openness of industrial networks implies that their sustainable development depends on the context in which they operate. Secondly, the methodology has to take into consideration both function and structure of the network at any point in time, whereby structural performance can only be assessed in the context of a particular function. Thirdly, the methodology has to be able to take into account the dynamics of industrial networks. Due to industrial networks being complex adaptive systems, their function and structure constantly change and at different stages throughout its evolution, the network can perform differently.

This chapter starts with an overview of different sustainability frameworks and their applicability to assess sustainable development of industrial network evolutions. On the basis of this discussion, it is argued that an evaluation of sustainable development of industrial network evolutions needs to consider their contribution to society, their efficiency and effectiveness and the resilient and adaptive nature of the system simultaneously and over the total timeframe of the analysis²⁰. On the basis of this observation, a set of indicators will be developed to assess sustainable development. The final section of this chapter is concerned with the question of how to compare different industrial network evolutions to each other. It is argued that a combination of scenario analysis and goal programming hold promise in this regard.

4.2 Sustainable development

In this thesis, sustainable development is defined as the process that describes the transformation of the current system state into a state of sustainability. In other words, sustainability is a difficult and distant goal, and sustainable development is a variable process of moving towards that goal (Dovers and Handmer 1992:275). As such, it refers to a process of 'creating what should be' rather than 'fixing what is' (Ehrenfeld

²⁰ Section 4.3.3 and 4.3.4 develop definitions for each these four structural features of industrial networks.

2007:78)²¹. However, the definition of a state of sustainability itself is a very elusive concept. The definition depends on the particular applications of the system, the priorities and vested interests of organisations involved, as well as on the scientific or political context in which the system functions (Voinov and Farley 2007:105). This means that what currently is perceived as sustainability is not necessarily similar to future perceptions of sustainability. Also, sustainability can only be defined if intergenerational options are translated into operational and normative concepts (Norton 1995:135). Furthermore, it is argued that sustainability is not an 'end-state', but instead refers to a set of principles that describe a dynamic system that is evolving and adapting over time (Korhonen 2004:810).

There are three major challenges in evaluating sustainable development in the context of industrial networks; all related to their complex adaptive system characteristics. Firstly, industrial networks are open systems. They act and interact with other subsystems in their socio-economic and biophysical environment, both in terms of inputs and outputs. Therefore, sustainable development of an industrial network depends not only on the system itself, but also on system inputs and outputs. Secondly, the multi-scale complexity of industrial networks means that sustainable development of subsystems (the organisations) do not necessarily equate to sustainable development of the system as a whole (the industrial network). Similarly, sustainable development of an industrial network does not equate to sustainable development of society.

In industrial networks, sustainable development is both a function of how the subsystems operate as well as how the subsystems are connected. This complex relationship between organisational behaviour, organisational relationships and industrial network performance has to be considered explicitly in an evaluation of sustainable development. Thirdly, industrial networks evolve over time through the adaptive and learning capacities of organisations. Chapters 2 and 3 have already discussed how decisions to invest in new technologies, choose new partners or innovate all affect the system performance as a whole. The consequences for the evaluation of sustainable

²¹ This definition of sustainable development is in sharp contrast to other definitions, which conceptual sustainable development in terms of reducing non-sustainable aspects of our current society (see for example Kaufmann and Cleveland 1995; Marshall 2005). At the same time, the founding principles of sustainable development, as articulated by the World Commission on Environment and Development (1987) remain valid,

development of industrial networks are that industrial networks cannot be evaluated as a state, but instead have to be evaluated on the basis of the evolutionary pathway that the industrial network takes.

This chapter argues that to accommodate these challenges, a framework to assess sustainable development of industrial networks has to take into consideration the complex features of industrial networks. Consequently, sustainable development can only be evaluated if all three features of industrial networks are considered simultaneously as follows:

- 1) What is the contribution of the industrial network towards the larger system in which it operates?
- 2) How efficient and effective is the industrial network in providing these contributions?
- 3) How resilient and adaptive is an industrial network in the light of future uncertainties?

In conclusion, an industrial network should provide needs of customers and society at large, it should operate efficiently and effectively within its environmental and social context, and it should be resilient and adaptive to shocks and shifts over time.

From a systemic perspective, the answer to each of these three questions depends on four features of the industrial network that can be distinguished on a systems level. These systemic features are the function, structure, context and governance of a system. Function, structure and context are three systemic characteristics that have been used to characterise the sustainability of ecological systems (Scholz and Tietje (2002) in Lang, Scholz et al. 2006). Governance is an additional feature required to reflect the agency of industrial organisations; their ability to change the function and structure of the system purposefully. These four aspects – function, structure, context and governance – can be used to reflect upon the function, efficiency, effectiveness, resilience and adaptiveness of industrial networks. For example, the contribution of an industrial network to the socio-economic system in which it operates depends on the function and the context of the system. However, the effectiveness by which the industrial network provides the desired functionality also depends on the structure of the system and how inputs are converted into the required functionality. Finally, the resilience and adaptiveness of a system does not only depend on the structure of the

network, but also how in how far the structure is affected by the decision making processes that take place.

In the context of this thesis, the importance of the interrelationship between functional, structural and dynamic features of industrial networks for evaluating sustainable development is twofold. Firstly, an assessment of interventions to stimulate sustainable development requires an assessment of both function and structure at any point in time throughout the network evolution analysed. Secondly, it requires explicit consideration of the importance of any of these features for sustainable development of industrial networks.

This chapter will proceed as follows. Firstly, the applicability of existing sustainability frameworks will be discussed, and how these frameworks relate to function, structure, context and governance of industrial networks. On the basis of this review of existing frameworks, a new framework is suggested that incorporates all the requisite systemic features of industrial networks. The second part of this chapter proposes a set of indicators that can be used to evaluate sustainable development of industrial networks. The last part of this chapter discusses how different evolutionary pathways can be compared to each other.

4.3 Existing frameworks for sustainable development

There are many frameworks for evaluating sustainable development available, and almost as many attempts to develop overarching decision support frameworks in which to place these. Furthermore, there is a lot of commonality between the different frameworks, which makes it difficult to categorise them into separate strands of thinking. The overview of frameworks presented in this section is an attempt to discuss representative frameworks and their applicability to industrial networks. As such, this overview focuses on those frameworks for sustainable development that take a systems approach, and discusses the advantages and disadvantages of their approaches to the evaluation of industrial network evolution.

4.3.1 A systems approach for assessing sustainable development

Systemic approaches to sustainability consider the relationships between three systems: the economic system, the human system and the natural system (Passet (1979) in

Munda 2005:956). The economic system includes economic and human activities, such as production, exchange and consumption. Given scarcity, the economic system is efficiency oriented. The human system comprises all activities of humans on this planet. The economic system can be seen as a part of the human system. Finally, the natural system comprises both the human and economic system (Munda 2005:956).

Jackson (1996) applied this systems approach to industrial networks, whereby sustainable development of industrial networks was placed within the context of the larger socio-economic and biophysical systems in which they operate. Firstly, sustainable development of industrial networks can be assessed by the needs they provide to society. Secondly, sustainable development of industrial networks can be assessed according to the quantity of natural resources that are used to provide societal benefit, and in how far into the future the industrial network can ensure the availability and use of high quality resources (p. 13). These principles are derived from the first and second law of thermodynamics and reflect the effects of industrial networks on the biophysical system (Jackson 1996). Furthermore, he argues that an evaluation should reflect not only the current contribution to society, but also the system's ability to provide. The advantage of Jackson's framework for assessing sustainable development of industrial networks is that it recognises that all three features need to be assessed simultaneously.

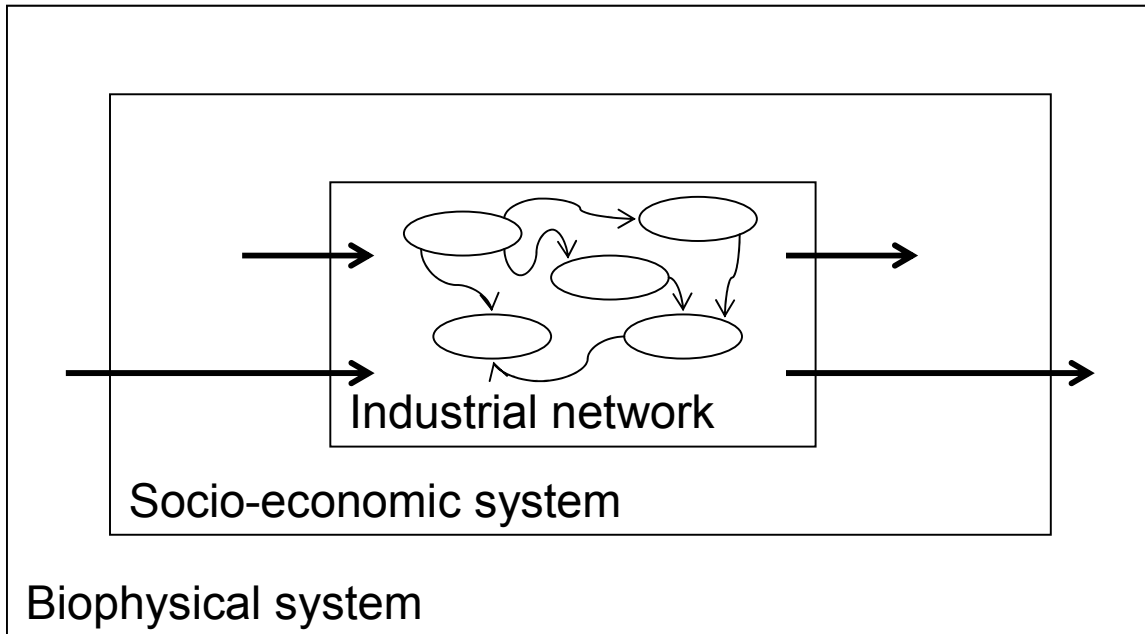


Figure 4- 1 The position of industrial networks in the context of socio-economic and biophysical systems

The next sections will discuss in some more detail how these three features should be considered and the different sustainability frameworks that have attempted to address some or more of these features. The advantages and disadvantages of the frameworks will be discussed.

4.3.2 Meeting society's needs

It has become common practice to evaluate the contribution of systems to sustainable development in three dimensions; *vis-à-vis* their social, environmental and economic contributions (Labuschagne, Brent et al. 2005:1). However, the question remains how to decide which products and services provide a positive contribution to society and which do not. The answer to this question is intrinsically linked to the stakeholders involved, either within industrial networks or within the socio-economic system in which the industrial network operates (Dovers and Handmer 1992:264). The assessment of industrial network contributions is of a moral or ethical nature (Funtowicz and Ravetz 1994:204). As such, any assessment that assumes particular needs for society is retrospective, since the assessment is based on experience of the past and the prevailing value set of the day (Ness, Urbel-Piirsalu et al. 2007:506).

This normative character of assessing sustainable development poses two challenges for the evaluation of industrial network evolutions. The first challenge is that the contribution of an industrial network is a function of the interaction between organisations. Since there is no single organisation that has control over all the activities of the network, it is impossible for an individual organisation to evaluate whether their individual contribution will have a positive contribution on a systems level. The second challenge is that during the timescale over which industrial network evolutions are evaluated (30-100 years), it is highly likely that the stakeholders (and their values) will change.

There are several sustainability frameworks developed that attempt to translate sustainability principles from a network perspective to guidelines for individual organisations. However, most of these do not address the complexity of interacting organisations in complex adaptive systems and are therefore less useful for evaluating industrial network evolutions. For example, Robert (2000) and Robert, Schmidt-Bleek et al. (2002) developed a generic framework to plan for sustainability, which relates different principles of sustainability to different system levels. Essentially, the framework attempts to take into consideration complexity by analysing different systems levels explicitly. The framework starts by stating sustainability principles for the global ecosystems, and tries to translate these principles to lower level systems including that of individual organisations. The final step is to translate these principles into tools that monitor and audit the actions of individual organisations through standards, guidance and protocols (Robert 2000:248). Examples of such frameworks are the Global Reporting Initiative (GRI 2006), United Nations Commission on Sustainable Development Framework (UN 2005), Sustainability Metric of the Institutions of Chemical Engineers (ICHEME 2007), and the Dow Jones Sustainability Index (SAM Indexes 2006).

The frameworks consist of a range of quantitative indicators that represent norms and values within which organisations have to operate. These indicators can be absolute (eg no child labour), relative (eg restrictive water use) or normative (eg promote community engagement). However, only if these criteria are absolute, is there any hope that system level performance will be equal to performance at the organisational level. For relative or normative criteria, this approach of developing organisational guidelines fails to

realise that “there is no evidence that a sustainable system is necessarily composed of sustainable parts” (Voinov and Farley 2007:110). Instead, the interdependency of industrial networks within a socio-economic system suggests that sustainability principles can be adhered to on an industrial network level without (necessarily) restricting all, or some, of the activities of the organisations which comprise the industrial network. For example, supply chains in the chemical industry can achieve higher energy efficiencies if they, instead of individually pursuing higher energy efficiencies, coordinate their efforts to achieve efficiency over the total supply chain (Kempener 2003). In terms of energy savings, supply-chain wide strategies can achieve up to 80% more reductions than individual organisations pursuing energy efficiency (Weizacker, Lovins et al. 1997). The difficulties of using organisational performance to evaluate the performance of industrial networks as a whole suggests that sustainable development of industrial networks should be evaluated on an industrial network level rather than on an organisational level. This sits in contrast to the recognition that performance at a network level is the sum of decisions taken at an organisational level.

The second challenge in evaluating the contribution of industrial networks towards sustainable development is that the normative framework in which any contribution is assessed will certainly change in the future. From a methodological perspective, this means that the normative framework to evaluate industrial networks is only valid in the near future and that long-term network evolutions cannot be assessed. On the other hand, if one wants to consider the effects of interventions on sustainable development of industrial networks it is important to take a long-term perspective and consider its consequences over the period that these interventions affect the network evolution.

In economic studies, this problem of intertemporal preferences is dealt with through discounting. By discounting the contribution of the industrial network is weighted by a discount factor, so that the further into the future a contribution occurs, the less importance is assigned to that contribution. Discounting could also be used in the opposite way by valuing higher those industrial networks that become increasingly more efficient or resilient. The use of discounting factors to evaluate sustainable development, however, is heavily debated by some scholars (Tol and Yohe 2006; Nordhaus 2007; Weitzman 2007), because the value of the discount factor either heavily favours or discredits those interventions that have a high cost, but long-term positive

consequences. The Stern report, for example, argues that discounting should only be used to reflect the possibility that the system will cease to exist in the future and therefore applies a very low discounting rate (Stern 2006:43). The larger the system, the more important it is to maintain its functionality into the future and the lower the discount rate should be, “possibly reaching zero at the level of the global ecosystem” (Voinov and Farley 2007:110). For industrial networks, this would mean that in evaluating their contribution to the larger socio-economic environment, discount rates can be used (with some caution) only to reflect the possibility that the industrial network will not be useful anymore in the future.

From this review, it can be concluded that the contribution of industrial networks to sustainable development has to be considered in terms of the socio-economic and biophysical system in which they operate. Furthermore, this assessment has to take into consideration that the definition of contributions is normative and depends on the stakeholders, the time of the assessment and circumstances under which the assessment is done. Finally, development of policies that assess system-wide performance of industrial networks are more appropriate than assessments of individual organisational performance.

4.3.3 Efficiency and effectiveness of industrial networks

Identifying the impacts of industrial networks on socio-economic and biophysical systems in which they operate is a necessary but insufficient step to evaluate their contribution to sustainable development. Efficiency and effectiveness are two other important features of sustainable development of industrial networks (Kaufmann and Cleveland 1995:109; Jackson 1996:14; Clark 2007:1737). Efficiency is related to the conservation laws of physics, which state that input in terms of energy and/or mass are equal to the output of a system in terms of energy and/or mass, excluding any accumulation. For industrial systems, this means that the mass of natural resources entering an industrial network is equal to the mass of products and services and the mass of waste (excluding stock formation within the system). A system is regarded as more efficient than another system if it transforms natural resources into the same or more goods and products with less waste. Effectiveness reflects the second law of thermodynamics, which states that, with any material or energy transformation, there is a loss in terms of ‘useful’ energy and an increase in the dissipation of materials through

the system. The interpretation of the second law of thermodynamics for industrial networks is more complex and far reaching than described here; however the concept of effectiveness can be used to reflect on an industrial network's ability to provide value. From this perspective, industrial networks that use high-value resources to produce low-value products are less effective than industrial networks that use low-value resources to produce the same products. Similarly, an industrial network that uses low-value resources to produce high-value products is more effective than an industrial network that uses high-value resources to produce the same products.

Two observations can be made with regard to efficiency and effectiveness as concepts for evaluating sustainable development. Firstly, the efficiency and effectiveness of industrial networks are independent characteristics of the system. A system that is very effective is not necessarily efficient and vice versa. Secondly, efficiency and effectiveness can only be used for evaluating different industrial network evolutions if the contributions of both industrial networks (their outputs) are comparable. In other words, efficiency and effectiveness can only be used as measures for sustainable development in the context of a particular contribution of the industrial network towards its wider environment (Ekins 1993:275).

The discussion on efficiency and effectiveness within the context of sustainable development is directly related to the perspective that, on the one hand, natural resources are limited; and on the other hand, the demand for goods and services is growing. The first studies that emphasised efficiency and effectiveness as core principles for sustainable development were the WORLD2 and WORLD3 models developed by Forrester (1971) and Meadows, Randers et al. (1972). These reports argued that sustainable development requires either reductions in growth of production/consumption or measures to increase efficiency and effectiveness of the socio-economic system (Randers 2000:213).

The concept of efficiency and effectiveness as drivers for sustainable development has also been taken up by other sustainability arguments. The Club of Rome, in their report Factor Four, emphasised that at least four times more wealth could be extracted from the material and energy we use globally (Weizacker, Lovins et al. 1997). Other sustainability concepts that focus on reducing the inputs are ecological footprint

(Wackernagel, Onisto et al. 1999), life cycle analysis (LCA) (Heijungs, Guinee et al. 1992; Azapagic and Clift 1999) and industrial ecology (Frosch and Gallopoulos 1992; Graedel and Allenby 1995; Ehrenfeld and Gertler 1997). The difference between 'Factor Four' (or eco-efficiency) and ecological footprint, as opposed to life cycle analysis and industrial ecology, is that the latter pairing focuses on the performance of systems as a whole instead of individual organisations. They are therefore more appropriate for analysis of the contribution of an industrial network to society as well as for analysing the efficiency and effectiveness in industrial networks. The use of life-cycle analysis for the development of indicators will be discussed in section 4.4.1.

4.3.4 Dynamics in industrial networks

Industrial networks are complex adaptive systems, which means that their contribution to society, as well as their effectiveness and efficiency, is constantly evolving through the actions and interactions of the organisations involved. This evolutionary process is not homogenous, but evolves through different stages of growth and decline, which are both necessary for successful system evolution (Jovanovic 1982; Holling 2001:395). For example, successful development of new innovations requires initially a stage of ferment with a large number of small organisations competing with each other followed by stages of incremental innovation with a small number of organisations operating in a stable environment (Rosenkopf and Tushman 1994:407; Vega-Redondo 1996). It follows from the dynamic features of industrial networks that an assessment of sustainable development has to do justice to the complexity of evolution, which comprises both contradicting and conflicting processes and requires both to be interspersed within an unified evaluation framework (David and Rothwell 1996).

There is a large variety of sustainable development concepts that explicitly deal with dynamics of systems and are embedded within notions of maintenance, sustenance or continuity of the system and its function (Voinov and Farley 2007:106). These definitions do not necessarily incorporate moral values about the functionality of the system, since normative values change over time. Furthermore, these definitions are less concerned with the efficiency and effectiveness of system operations. Instead, these concepts focus on structure as the main system feature that allows system to develop and evolve continuously. Examples of indicators for structure include Shannon Information, Gini-

Simpson Information and Fisher Information and these indicators are widely applied in ecological systems (Limburg, O'Neill et al. 2002; Cabezas, Pawlowski et al. 2004).

More recently, these structural indicators have also been applied to socio-economic systems (Dovers and Handmer 1992; Costanza, Wainger et al. 1993; Arrow, Bolin et al. 1995; Folke, Carpenter et al. 2002). In particular, resilience has been mentioned as a system feature that contributes to sustainable development of an industrial network. Initially, resilience was defined as the ability to absorb changes to key variables and parameters (Holling 1973:14). In the meantime, many authors have picked up on resilience and its importance in assessing sustainability. The next table provides some of the definitions of resilience applied to socio-economic systems, like industrial networks.

Table 4- 1 Several definitions of resilience for applications in socio-economic systems

Author	Definition
(Holling 1973)	Resilience is a measure of persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables [...]. Stability is a different property, which represents the ability of a system to return to an equilibrium state after a temporary disturbance (p. 14).
(Dovers and Handmer 1992)	There are three types of resilience: a) characterized by the maintenance of status, b) incremental change and adjustment at the margin and c) flexibility and openness in response to change (p. 270).
(Costanza, Wainger et al. 1993)	Resilience implies the system's ability to maintain its structure (organisation) and function (vigor) over time and in the face of external stress (p. 552).
(Arrow, Bolin et al. 1995)	Resilience is a measure of the magnitude of disturbances that can be absorbed before a system centered on one locally stable equilibrium flips to another (p. 93)
(Limburg, O'Neill et al. 2002)	Resilience is how quickly a distributed system returns to its equilibrium (p.410). Resilience has two components: a) the length of time it takes a system to recover from stress, b) the magnitude of the largest stress from which the system can recover ultimately (p. 411).
(Folke, Carpenter et al. 2002)	Resilience can be characterized by three characteristics: a) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction, b) the degree to which the system is capable of self-organisation (versus lack of organization, or organisation forced by external factors) and c) the degree to which the system can build and increase the capacity for learning and adaptation (p. 4).

(Thadakamalla, Raghavan et al. 2004)	Resilience defined as 'survivability' of industrial networks with the following four components: 1) robustness (connectiveness under attack), 2) responsiveness (low characteristic path length), 3) flexibility (presence of alternative paths) and 4) adaptivity (ability to rewire efficiently) (p.24-25) .
(Allenby and Fink 2005)	Resilience is the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must (p. 1034).
(Fiksel 2006)	Resilience is the capacity of a system to survive, adapt, and grow in the face of turbulent change (p. 16).
(Nelson, Adger et al. 2007)	Adaptiveness is the outcome of a resilient system through a process of incremental system adjustments and deliberate transformations. Characteristics of resilient systems are 1) self-organisation, 2) capacity to learn and 3) capacity to to absorb change (p. 400).

The definition of resilience shows paradoxical characteristics. One dimension of resilience reflects the system's ability to maintain a particular functionality, while the other dimension refers to the system's ability to adapt its functionality to future changes in the larger socio-economic system in which it operates. The first dimension reflects an ecological perspective, where resilience mostly refers to the capacity of a system to retain or maintain its functionality if affected by shocks, stresses and/or attacks (see type 1 resilience of Dover and Handmer (1992), or the first component of resilience by Folke, Carpenter et al. (2002)). The second dimension of resilience is mentioned more recently (Hooker 2007; Nelson, Adger et al. 2007) and could be characterized as adaptability; the system's capacity to change its functionality in the light of permanent changes in the internal structure or external environment of the system.

The second observation that can be made is that different authors describe different external events impacting on the system. On the one hand, some authors point to temporary changes that impact on the system's ability to maintain its function, but after which the external environment will return to its initial conditions (Holling 1973; Arrow, Bolin et al. 1995; Limburg, O'Neill et al. 2002). Other authors highlight the effects of permanent changes in the environment, which implies that the system has to adapt its functionality to accommodate the changed requirements of the new environment (Dovers and Handmer 1992; Folke, Carpenter et al. 2002; Nelson, Adger et al. 2007). These two different external changes, referred to in this thesis as shocks and shifts

respectively, both impact on an industrial network, but require different responses from the system. If the change is a shock, the system will have to maintain its functionality by re-arranging the structure such that output is maintained. However, if the change is a shift, the system will have to change functionality to accommodate the requirements of their environment. These two system responses towards external changes can take completely different shapes. For temporal shocks, the system requires excess capacity in terms of resources, production facilities and organisations in order to maintain provision of particular goods and services. For permanent shifts, the system requires the ability to change to or use new resources, production facilities and organisations that can provide the new functionality required.

Parallel concepts for the distinction between resilience and adaptiveness can be found in process systems engineering. In process systems engineering, 'operationability' includes consideration of flexibility to accommodate variable input or output streams (adaptiveness), while controllability refers to the robustness of the system (resilience) towards shocks either internally or externally to the system (see for example Bahri, Bandoni et al. 1997). The tension between maintaining functionality and being able to adapt its functionality features also in discussions on social networks (Ng 2004) and ecological systems (McCann 2000). Since these two system responses have different requirements for the structure and governance of systems, it is argued here that a distinction should be made between the resilience of an industrial network and the adaptiveness an industrial network. As such, resilience is a system's ability to maintain its functionality through temporary shocks, while adaptiveness is a system's ability to adapt its functionality to permanent shifts in the environment.

Finally, the literature reviewed in this section suggests little coupling of the concepts of resilience and adaptiveness to concepts discussed in previous sections (a systems contribution and the efficiency and effectiveness by which these contributions are provided). Only recently, scholars have attempted to couple concepts of resilience to other sustainable development concepts. For example, Sartorius (2006) argues that sustainable development, and in particular the role of innovation within sustainable development, can be expressed in terms of first-order and second-order sustainable development. First-order development refers to the production of a particular output with less inputs, while second order development represents an evolutionary perspective that

requirements and needs can change in the future and therefore fostering radical innovation is a means of safeguarding the continuation of society (Sartorius 2006:278). Furthermore, Hooker (2007) distinguishes two dimensions of sustainability. One dimension of sustainability is based on values with regard to not hurting things (eg stop dumping waste) and maximising use. The other dimension is defined as adaptive resilience, which is the capacity to continue the system by adapting in the face of change (Hooker 2007). Hooker's definition of adaptive resilience is equal to the definition of adaptiveness applied in this thesis.

Both the concepts of sustainable development developed by Sartorius and Hooker are important contributions to the development of a holistic approach for evaluating sustainable development of industrial networks. Their approaches not only reflect industrial networks as nested systems within wider socio-economic and biophysical systems, but also reflect the complex nature of industrial networks as complex adaptive systems. A holistic approach for evaluating sustainable development of industrial networks, incorporating views on the industrial network contribution, its efficiency and effectiveness as well as its resilience and adaptiveness is essential for evaluating industrial network evolutions.

4.3.5 Preliminary conclusions

The four previous sections of this chapter have discussed different aspects of sustainable development and how each of these aspects is important for evaluating sustainable development of industrial networks. It was argued that the contribution of industrial networks should be evaluated on a systems level, reflecting social, environmental and economic contributions. These particular contributions form the context within which it is possible to evaluate the efficiency and effectiveness of industrial networks and the resilience and adaptiveness of their structures.

The next section of this chapter will operationalise the holistic approach advocated here into a set of indicators for quantifying sustainable development of industrial network evolutions. Subsequently, different multi-criteria decision analysis (MCDA) techniques are suggested for garnering stakeholder preferences and value judgements within the overall evaluation of sustainable development of industrial networks.

4.4 Indicators for evaluating sustainable development

The previous section has argued that an evaluation of sustainable development in industrial network should consider the needs provided to customers and society a large, the efficiency and effectiveness by which the system operates and the systems resilience and adaptiveness to shocks and shifts over time. This section uses these dimensions of sustainable development to suggest a set of indicators that can be used to assess sustainable development of different network evolutions. The final aim of this section is to be able to quantitatively compare different network evolutions and to be able to assess how interventions have positively or negatively contributed to one or more of the sustainability criteria identified in the previous section.

The sustainability frameworks discussed in the previous section have in many cases already suggested indicators for the quantification of their sustainability concepts. This section will select the appropriate indicators and illustrate how they can be applied in the context of industrial networks. A simplified version of the case study presented in chapter 6 is used to illustrate the use of indicators to evaluate sustainable development. On the basis of these indicators, the final section of this chapter will discuss how these different indicators can be related to each to provide a holistic analysis of sustainable development.

4.4.1 Indicators for evaluating industrial network contributions

A large number of sustainability indicators have been developed in recent years, often categorised in economic, social and environmental criteria. Examples of economic criteria are financial health (equity), economic performance and trading opportunities; environmental criteria address the use of air, water, land mineral and energy use (including their contributions in terms of emissions); and social indicators range from labour safety to stakeholder empowerment. The particular contribution with regard to sustainable development depends on the stakeholders involved and can be different for different systems. For example, the case study of a bioenergy network discussed in chapter 6 is evaluated according to three indicators: the number of households electrified, the economic value added and the amount of CO₂ emissions associated with the production of energy. These three indicators represent different interests of the stakeholders involved in the development of this network.

If one considers sustainable development of industrial networks as a whole (ie from the perspective of an analyst or group of stakeholders interested in a network evolution), three criteria need to be fulfilled. Firstly, as argued in section 4.3.2, if the indicators are expressed in relative terms (ie more or less of a particular functionality), they should be measured on an industrial network level rather than an organisational level. Secondly, indicators should not only reflect the contribution of an industrial network at the end of their evolution, but also reflect the contribution that industrial networks make throughout their evolution. Thirdly, indicators should allow for a comparison between different network evolutions in order to determine which evolution has contributed more or less to sustainable development.

Several techniques have been developed to assess the contribution and/or functionality of a system consisting of multiple subsystems. In 1969, the World Energy Conference presented a methodology that allowed assessing the energy use associated with the entire production process from cradle to grave of a particular product (Boustead 2000:34). The methodology was standardised in 1974 at the Energy Analysis workshop in Sweden as the IFIAS-standard. In the meantime, several other methodologies have been developed to assess energy and environmental impacts associated with the production of goods and services over the total life-cycle of the product, most notably Life-Cycle Analysis. These methods can also be used to assess the economic and social performance of industrial networks by aggregating the impacts of industrial networks over all the organisations that play a role in the functioning of the network. It is suggested here that indicators used to evaluate such a contribution should be based on a life-cycle approach, whereby the total contribution of a network is evaluated on the basis of the impacts associated with all organisations that are present in the industrial network. Taking the case study of a bioenergy network as an example, this implies that the economic value of the system is measured according to the economic contributions of all organisations involved and that emissions are measured on the basis of energy use for the production of electricity and biofuels, emissions associated with the transport of biomass as well as emissions that are prevented by replacing coal-fired electricity or petrol fuels.

The second criterion for the development of indicators of industrial network evolution is that they reflect the contribution of the pathway rather than the end state of the system.

This is vitally important and, as such, the contribution of industrial network evolutions should be evaluated at any point in time throughout their evolution to reflect the value of different pathways and their associated contributions to the socio-economic pathway in which they operate. By integrating the contribution overall the whole analysis period, a more accurate representation can be made about sustainable development of these different evolutions.

The third criterion for the development of indicators of industrial network evolutions is their ability to compare contributions across different network evolutions. Different techniques have value here. Whilst direct comparison may be possible, application of a range of MCDA techniques, using either local or global ranges against which to normalise performance data, is more meaningful. Goal programming on the basis of particular aspiration levels is particularly attractive, especially where thresholds are set above the best performance of the network. Under such circumstances, the indicator would reflect contributions above this threshold do not necessarily constitute industrial networks that are preferred in terms of sustainable development. For example, a bioenergy network that provides more energy than required for the region in which it is situated is not more sustainable than a bioenergy network that fulfils the regional needs. In this case, the value of the evolution does not only depend on a comparison of contributions of the different network evolutions, but how the network evolution compares to the needs associated with the socio-economic system in which they operate. In this thesis, the value of the contribution is measured comparing the relative contributions of different network evolutions to each other according to the needs of the socio-economic system in which the network operates. These techniques will be discussed in more detail in section 4.5.

In this thesis, there are three reasons for explicitly comparing the different network contributions to each other at discrete states throughout their evolution. The most important reason is that each system state has different structural features. If one wants to compare both the contribution of an industrial network as well as its features in relation to sustainable development, the analysis has to consider each state separately. The second reason is to reflect the impact of infrastructures and how they affect the different pathways of network evolution. An overall comparison does not reflect how infrastructure and other lock-in effects can impact on the network evolution as a whole.

The third reason is that the case study focuses on an industrial network that is currently not yet operational. From this perspective, those interventions that stimulate development of such network at an early stage are preferred over interventions that take a long period of time to come into effect. By using a yearly ratio to evaluate the systems performance, those industrial network evolutions that provide contributions in an early stage are valued better than other networks that take a long time to start off.

Box 4.1 The sustainability contribution of a bioenergy network

This example considers three different bioenergy network evolutions, represented in figure 4-2.

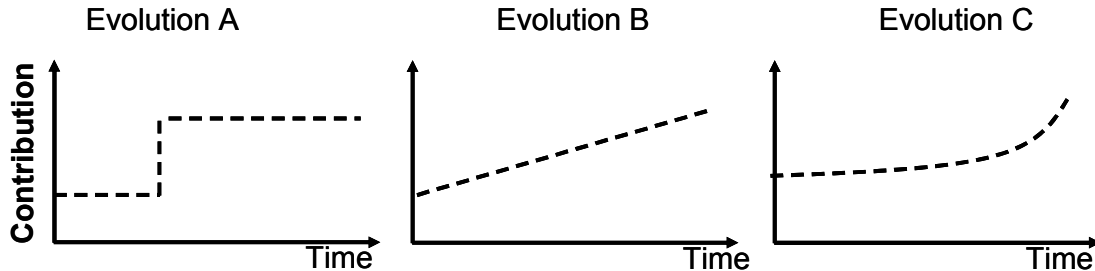


Figure 4- 2 Three different network evolutions

The contribution of these networks is measured in terms of MWh of electricity produced. Each network evolution has a different pathway of development. Their contribution corresponds to the different pathways they follow. Table 4-2 illustrates two different ways of assessing the contribution of the three network evolutions presented here.

Table 4- 2 Evaluation of different industrial network evolutions

year	A	B	C	maximum	value A	value B	value C
1	1	1	1	1	1.0	1.0	1.0
2	1	2	1	2	0.5	1.0	0.5
3	1	3	2	3	0.3	1.0	0.7
4	1	4	2	4	0.3	1.0	0.5
5	1	5	3	5	0.2	1.0	0.6
6	10	6	4	10	1.0	0.6	0.4
7	10	7	6	10	1.0	0.7	0.6
8	10	8	8	10	1.0	0.8	0.8
9	10	9	12	12	0.8	0.8	1.0
10	10	10	16	16	0.6	0.6	1.0
total contribution:	55	55	55	total value:	6.7	8.5	7.1

Column A, B, and C represent the contribution of industrial networks throughout the first 10 years of their development. If one considers the total contribution of these different evolutions over the timescale of analysis, they all perform equally in terms of their contributions. However, if one compares the contributions of these evolutions on a yearly basis, using a local range from 0 to maximum contribution, the evaluation suggests that evolution B is preferred over the other two system evolutions. Using a yearly evaluation rather than an evaluation on the basis of the total contribution allows differentiating between different pathways and is therefore preferred. However, care should be taken in choosing a particular technique to compare the different network contributions.

4.4.2 Indicators for efficiency and effectiveness of industrial networks

Indicators for efficiency and effectiveness are well established in physics and engineering sciences. In the context of industrial networks, efficiency can be represented as the ratio of input quantity and output quantity, while effectiveness can be represented as the ratio of input quality versus output quality. In engineering systems, there is often only one system output (ie a product) which can differ both in terms of quantity and quality; however, in the case of industrial networks there are multiple outputs possible and their qualities depends on the perceptions of the different stakeholders involved in evaluating system performance. The input into industrial networks is the quantity and quality of resources entering the network, including resources required to process the natural resource into products and services. However, as argued in section 4.2.3., the efficiency and effectiveness of a system can only be evaluated in the context of one specific contribution of the industrial network. In other words, each contribution of the industrial networks can be delivered with different efficiencies and effectiveness. As such the following two indicators for efficiency and effectiveness are adopted.

For efficiency:

$$efficiency_{ind} = \frac{contribution}{resource\ input} \quad (4-1)$$

where the efficiency indicator is determined by the quantity of a particular contribution divided by the quantity of natural resources required to provide that particular functionality.

For effectiveness the following indicator is used:

$$effectiveness_{ind} = \frac{economic\ value\ contribution}{total\ value\ system} \quad (4-2)$$

where the quality of output and the quality of input are expressed in monetary terms. A discussion on the units of these indicators follows in the next paragraph.

The use of stakeholders to determine and define outputs contributing to sustainable development implicitly attaches a value to these outputs. In other words, each output indicator represents simultaneously a quality measure of the system's performance. Consequently, the measures of efficiency and effectiveness are specifically related to a particular contribution. In other words, an industrial network has different efficiency and effectiveness measures for the different contributions it makes towards sustainable development. However, this approach has some implications for the development of indicators of both efficiency and effectiveness. To measure efficiency and effectiveness, the units for measuring both quality and quantity of inputs need to be equal to the units of the indicator used to measure the output. For complex systems, this can be a challenging task. It is difficult to express different natural and capital resources in the same unit. To address this, it is suggested here that measurement of efficiency can be simplified by evaluating only the natural resource inputs, so that a direct comparison can be made between the quantity of units entering the systems and the quantity exiting the system²². For measuring effectiveness, this task becomes even more cumbersome, because the quality of inputs in terms of natural resources, production facilities and infrastructure available within the system have different values to different stakeholders. To circumvent the difficulties associated with developing a single indicator for representing the quality of all inputs and outputs, this thesis has simplified the effectiveness indicator by expressing the value of both inputs and outputs in monetary values. The monetary values associated with different inputs and outputs serve as a proxy indicator for their quality. However, it should be recognised that such an approach is a simplification of reality and if possible, other indicators should be developed to represent the effectiveness of industrial networks. The operationalisation of these indicators is described in chapter 6.5.4.

4.4.3 Indicators for resilience and adaptiveness of industrial networks

Section 4.3.4 discussed a number of different definitions for resilience. It was argued that the concept of resilience, as used in literature, actually consists of two different system characteristics that might be conflicting in terms of requirements for the system structure. A system that needs to maintain its functionality when faced with temporary shocks requires the ability to change its structure such that the production of goods and

²² Capital resources entering the network are captured in the effectiveness indicator.

services is continued. On the other hand, a system that is faced with permanent shifts in its environment, either through physical changes or by changed preferences of stakeholders, needs the ability to adapt its system such that a new functionality can be provided with the subsystems currently in place. It is argued here that two different indicators are required. The indicator for resilience has to measure the system's ability to maintain function in the face of temporal shocks, while an indicator for adaptiveness has to reflect the system's ability to provide new functionalities in the face of permanent shifts in its environment.

4.4.3.1 Measuring resilience

The development of indicators for resilience can be divided into three categories. One group of scholars has tried to develop an indicator for resilience by the length of time it takes to recover from a shock, and the magnitude of shock from which a system is able to recover (Pimm 1984 and Holling 1986 in Limburg, O'Neill et al. 2002:411). The second group has tried to develop indicators for resilience by looking at the structural features of systems using network theory (Carlson and Doyle 1999; Strogatz 2001; Newman 2003; Shargel, Sayama et al. 2003; Thadakamalla, Raghavan et al. 2004). The third category of indicators for resilience is related to diversity. Several indicators have been developed to measure diversity in systems, mostly in ecological studies. However, measures of diversity have also been applied to economic systems (David and Rothwell 1996; Britto 1998; Kauffman 2000; Cabezas, Pawlowski et al. 2004; Ng 2004; Tisdell 2004; Drechsler, Grimm et al. 2007).

The first two approaches for evaluating resilience are insufficient for the analysis of resilience in industrial networks. According to Kaufmann and Cleveland (1995), measuring the absorbance of disturbances (ie the time it takes for a network to recover from a shock) is not a meaningful way of measuring resilience, because it is impossible to know which parts of the system should remain in equilibrium and which parts should be adjusted to accommodate the threat of the disturbance (Kaufmann and Cleveland 1995:111). The shortcomings of this approach for analysing resilience in industrial networks become even more evident if one considers that the response towards a shock completely depends on the strategic behaviour of organisations at that particular point in time. It is not possible to develop an indicator that reflects the potential response of organisations to an unknown shock.

The second approach, using structural indicators to measure the resilience of industrial networks, is also not appropriate, because it ignores the intrinsic differences between different nodes and different relationships in industrial networks. Network theory regards each node and each link as being equal, except for the number of connections. However, in industrial networks some organizations have a more critical function than others and the ability of the system to maintain these critical functions should be reflected in the use of any specific indicator. Secondly, network theory assumes a static structure, while industrial network structures are a function of the individual decision making processes of organizations and can change at any point in time to accommodate for the loss or gain of organizations. Thirdly, network theory does not capture that some relationships can be unilateral (products can only go from suppliers to buyers and in essence not vice versa), while other relationships are bilateral (exchange of products between different suppliers). These different relational characteristics affect the function of the system and therefore its ability to maintain its functionality throughout shocks.

The third approach that is used to evaluate resilience is diversity. In ecological studies, diversity relates the number of different species in an ecosystem, while in socio-economic systems diversity has been used to reflect the diversity in organisations (Weisbuch 2000), the diversity of technologies employed (Stirling 2007), or insitutional diversity of industrial networks, reflecting the different forms of contracts between organisations and governance forms within the system (Britto 1998). A more detailed discussion of indicators for diversity will take place in the next section on adaptation, because it is argued here that, for an industrial network to maintain its functionality, it does not necessarily require a large diversity of different organisations, different technologies or different institutional features. This assertion is made on the basis of the following reasoning: in ecological studies, resilience refers to maintaining the functioning of the ecosystem regardless of its relationship to the wider system in which it operates. As such, an ecosystem can be seen as an independent system that needs to be maintained for the sake of its survival. Under these circumstances, diversity is important because an increased number of species increases the likelihood that the ecosystem can survive through external disturbances.

Industrial networks, on the other hand, cannot be viewed as independent systems. Their function is directly related to the wider socio-economic and biophysical system in which they operate and which provides their legitimacy. Resilience, in the case of industrial networks, therefore refers to maintaining the functionality that industrial networks provide to the larger system in which they operate and not to the survival of the industrial network itself. Under these circumstances, diversity might contribute to the system's ability to provide a particular functionality if the diversity is directly related to the number of options that an industrial network possesses in order to maintain the provision of a particular good or service, or the extent to which an industrial network has redundancy built into the system. However, a diverse number of organisations or a diverse number of technologies does not necessarily reflect resilience in industrial networks.

In conclusion, it is argued that, based on literature observations, conventional indicators for resilience do not reflect an industrial network's ability to maintain functionality under external shocks. Therefore, this thesis adopts a new indicator, which attempts to capture two features of industrial networks that contribute to its resilience: 1) redundancy and 2) alternative pathways. The indicator attempts to reflect the following two observations:

1. A network that has excess capacity is more resilient than a network that operates on full capacity (redundancy).
2. A network that has multiple organisations able to provide a particular functionality is more resilient than a network that has only 1 or a few organisations that can provide a particular functionality (alternative pathways).

The following indicator is constructed to capture both arguments:

$$R_t = \left(\frac{P_t - C_t}{P_t} \right) \cdot \left(\frac{N_t - 1}{N_t} \right) \quad (4-4)$$

where C_t stands for the contribution provided at time t , P_t is the potential contribution that could have been provided if all capacity was used and N is the total number of organisations providing the functionality at time t . The indicator becomes 0 if there is no access capacity (the first term reduces to 0) or if there is only 1 organisation providing the functionality (the second term reduces to 0). Resilience approaches 1 if there is large

excess capacity and a large number of organisations are able to provide the functionality²³.

The potential capacity can be calculated by summing up the potential contribution each organisation at time t can make by multiplying its particular capacity with its individual efficiencies to produce a particular contribution.

$$P_t = \sum_{r=1}^{N_t} (c_{rt} \alpha_{rt}) \quad (4-5)$$

where c_{rt} is the capacity of organisation r and α_{rt} is the organisation's efficiency at time t . N is the total number of organisations that can provide a particular functionality.

The first part of the indicator (eqn 4-4) attempts to address the redundancy of a system in terms of the natural resources it has available to it, or the production facility that is available. Redundancy has been used in ecosystems to the fitness of species rather than the diversity of species (Walker 1992:18), while in engineering studies redundancy refers to the systems ability to deal with unexpected failures within the system. The parallel here is that redundancy in the case of industrial networks refers to the network's ability to maintain the provision of a particular contribution if the delivery of resources or part of the production capacity fails temporarily. The second part of the indicator attempts to indicate the alternative pathways available to the system. If a particular resource required to provide the functionality of the system is owned by only one organisation, the system is more vulnerable to shocks affecting either resources, nodes or links in the system. On the other hand, if there are multiple organisations that can provide a similar function within the system, the industrial network is more resilient and able to maintain its provision of goods and services to the larger system in which it operates.

It is worthwhile to couch the definition of this indicator in terms of the case study described in Chapter 6. One can consider two different evolutionary pathways of a

²³ This indicator does not reflect the 'balance' in the network. Referred to as 'evenness' in ecology and 'concentration' in economics, balance refers to an even distribution between organisations (Stirling 2007: 9). From this perspective, a network that consists of two organisations with equal capacity is more resilient than a network that consist of two organisations, but where one organisation is larger than the other. Balance will be addressed in more detail in the discussion of indicators for adaptiveness.

bioenergy network: one with a centralised power plant and another where the individual sugar mills produce electricity locally. A centralised power plant will have higher efficiencies and therefore the potential to produce more energy. However, it is more vulnerable in terms of its resilience towards temporary failures in the production capacity of the centralised plant. On the other hand, a decentralised network might have lower efficiencies, but a larger number of alternative pathways. This trade-off between increased efficiency and alternative pathways is reflected in the resilience indicator. The application of the resilience indicator is described further in chapter 6.

4.4.3.2 Measuring adaptiveness

Adaptiveness in industrial networks and/or socio-economic systems requires the ability to provide new functionalities, because for these systems the function is dependent on the context in which the system operates. A clear example is the increasing interest in an electricity system associated with reduced CO₂ emissions. This means that electricity systems need to be able to change from the current system into systems that provide green electricity rather than grey electricity. From this perspective, it has been argued that diversity is the main indicator for adaptiveness of industrial networks and other socio-economic systems (see for example Allen 2001; Hooker 2007). Allen (2001) defines the relationship between diversity and adaptiveness as follows: “For a system to survive as a coherent entity over the medium and long term, it must have a number of internal states **greater** than those considered requisite to deal with the outside world“ (Allen 2001:175, original emphasis).

In general, three aspects of diversity are distinguished: 1) variety, 2) the balance between the different components and 3) the difference between different components. Each is a necessary but insufficient property of diversity (Stirling 2007:9). Variety is often parameterised by counting the number of different elements in the system; balance is parameterised by taking into consideration the distribution of the different species over the whole population (ie by statistical variance or ratios); and disparity is measured by the manner and degree to which different species can be distinguished. Stirling (2007) has developed an indicator that encompasses all three aspects of diversity using the following equation (Stirling 2007:18):

$$D = \sum_{ij(i \neq j)} d_{ij} p_i p_j \quad (4-6)$$

Whereby p_i and p_j are proportional representations of component i and j and d_{ij} is the difference in attribute between i and j (p. 18). The summation is across the half-matrix of $((n-1)^2/2)$ non-identical pairs of n elements ($i \neq j$). Applied to industrial networks, this results in a matrix comparing each organisation to any other organisation in the network. Each organisation is compared on the basis of its proportion and on the basis of different input resources, technologies and goods used and supplied by that particular organisation. Variety is measured by the number of organisations in the network (the number of organisations i) and balance is measured by the organisation's individual contribution to the total contribution of the network (p_i). Disparity between different functions is assessed according to three characteristics: 1) the resources entering the organisation, 2) the transformation processes employed by the organisation and 3) the products or services leaving the organisation. Depending on the context in which the industrial network is evaluated in terms of diversity, the number of organisations and the disparity characteristics differ. An example is provided in box 4.3.

Box 4.3 Diversity in industrial networks

A simple example is provided on how to measure diversity in industrial networks and the relationship between diversity and resilience and adaptiveness. Figure 4-3 provides four simple industrial network configurations. Network A and B have the same capacity, but A) consists of one manufacturer, while B) consists of two smaller manufacturers. Network configuration C and D are also equal in terms of production capacity, but C consists of a supplier and a manufacturer and D consists of two suppliers and two manufactures.

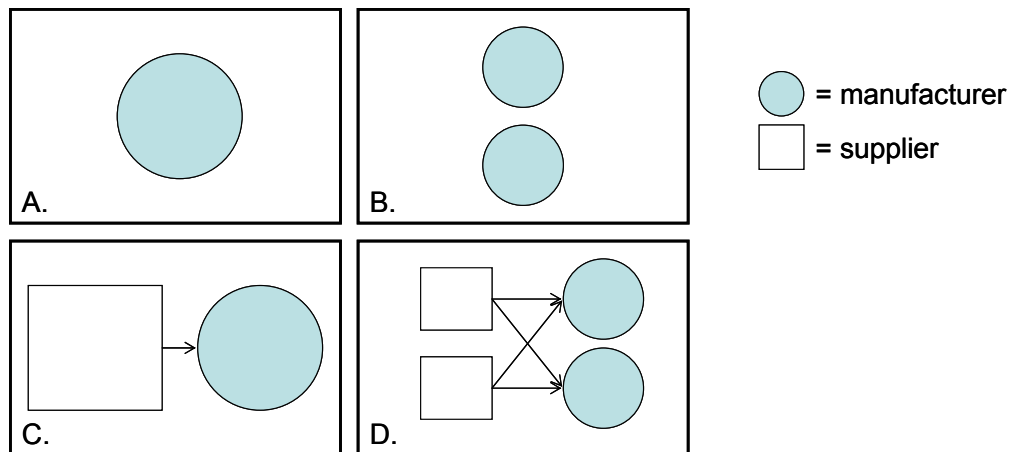


Figure 4- 3 Diversity in four different network configurations

Both network A and network B have a diversity index of 0, since they both consist of one species with exactly identical features. This means that both systems are equally adaptive to changes in the environment. However, it can be argued that network B is more resilient than network A, since a failure of one of the manufactures still results and the systems ability to provide a particular contribution. Network C and D have a diversity index of 0.5, since they consist of two species with different characteristics. In case of permanent changes internal or external to this industrial network, both network C and D are more adaptive than network A and B, because they have multiple species. However, as is the case between network A and B, it can be argued that network C is less resilient than network D, which would not have been indicated by diversity as a measure of resilience.

By introducing two additional terms, Stirling developed a heuristic on the basis of this indicator, allowing judgement for the importance of variety, balance and disparity depending on the environment in which the system operates:

$$\Delta = \sum_{ij(i \neq j)} (d_{ij})^\alpha (p_i p_j)^\beta \quad (4-7)$$

By allowing α and β to permeate between 0 and 1, the heuristic can cover all four properties of interest: balance, variety, disparity and diversity. The value of α and β depends on the analyst's interests and values for each of these characteristics. An application of the diversity index is shown in chapter 6 and the results are shown in chapter 7.

4.5 Measuring sustainable development

This previous section has developed a set of indicators for measuring the contribution of industrial networks to the socio-economic and biophysical systems in which they operate, as well as indicators for the efficiency and effectiveness by which these contributions are provided, and the resilience and adaptiveness of the system structures that provide these contributions. This section discusses how the different indicators for both functional and structural characteristics can be used to assess and compare different industrial network evolutions to each other. It should be stressed that the indicators developed only can be used to compare sustainable development of two different evolutionary pathways of one and the same industrial network.

For a systemic analysis of sustainable development of industrial network evolutions, the functional indicators for sustainable development have to be related to the structural indicators. The functional indicators are referred to as normative, to highlight that they represent the analyst's value set as to what are important to the industrial network's contribution to sustainable development. Secondly, the state performance of an industrial network at any point in time has to be related to the overall performance of industrial network evolution. The methodology consists of three steps.

Firstly, the structural indicators should be related to the normative basis in which context they have been evaluated. However, there are conflicts between normative and structural performance criteria. For example, a system that is resilient is often not as efficient as a system that is less resilient. Similarly, diversity and effectiveness can be conflicting characteristics as criteria for sustainable development. The same conflicts can be found between the normative contributions of industrial networks. A system that provides more social contributions might result in reduced economic performance. Multi-

criteria decision analysis (MCDA), besides its usefulness in representing decision making processes involving multiple criteria discussed in chapter 3, can also be used to resolve conflicts between objectives and is especially useful for evaluating the multidimensional concept of sustainable development (Munda 2005:955). This fact is pursued in this thesis.

Several techniques are available to compare conflicting objectives by explicitly considering the value functions and preferences of the stakeholders involved. Munda (2005) and Polatidis, Harambopoulos et al. (2006) provide an assessment of different MCDA tools in terms of their ability to reflect the philosophical basis of sustainability. For example, cost-benefit analysis allows for complete compensation between different contributions; in other words, full substitutability between different evaluation criteria. As such, it is consistent with a view of 'weak' sustainability, in which natural resources can be replaced by man-made resources with equal value. At the other extreme is the MCDA method of outranking, that incorporates veto thresholds above or below which an increase in one criteria cannot substitute a decrease in another criteria, regardless of the value subscribed to each of these criteria. Outranking is therefore consistent with a view of 'strong' sustainability, which suggests that natural resources have intrinsic values that cannot be expressed in economic terms. Value function approaches which are often only partially compensatory in nature, fall mid way between these two (see figure 4-4).

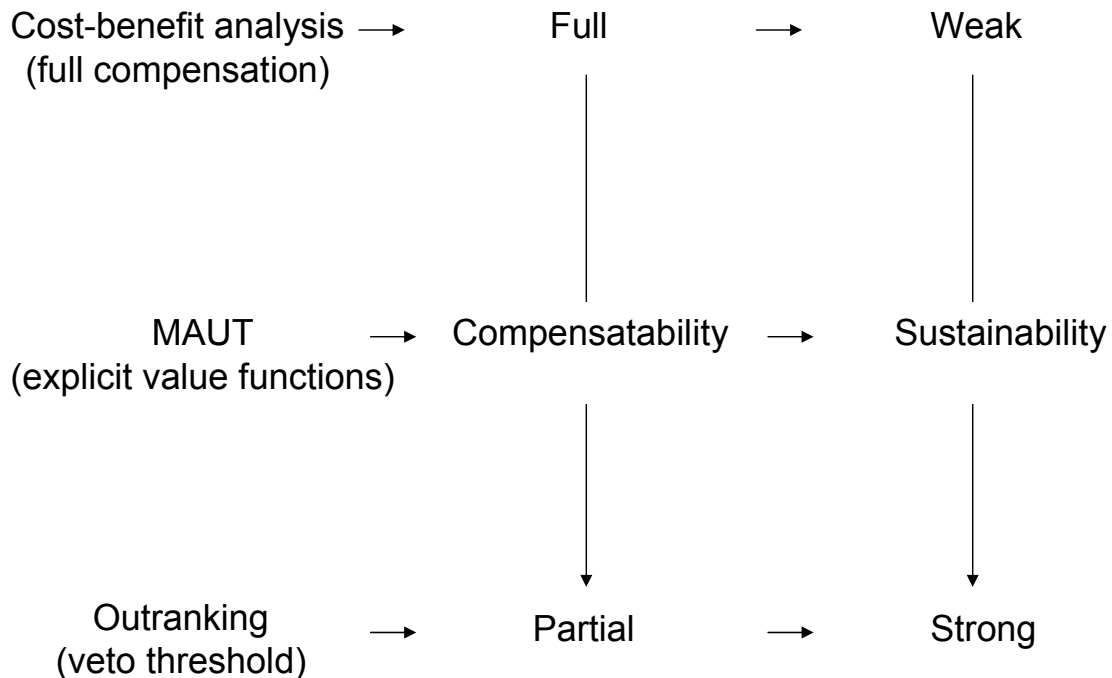


Figure 4- 4 Different MCDA techniques related to different views on sustainability

MCDA allows for comparing conflicting objectives like efficiency and adaptiveness, and thus enables evaluation of the structural value of a particular industrial network evolution in the context of a particular contribution. A comparison of different structural features needs to satisfy three conditions and requires two sets of information (Belton and Stewart 2002). The three conditions are 1) there is preferential independency between the criteria, 2) interval scales need to be constructed in order to be able to compare the different criteria and 3) weights are required to reflect trade offs between criteria. For the analysis of structural features of industrial networks this means that 1) local or global scales with associated value functions need to be constructed for each of the indicators²⁴ and 2) importance weights for each indicator are specified. The local scale for each industrial network can be found by creating an interval scale of best and worst value for each indicator over all the industrial network evolutions that have been evaluated. This means that the evaluation of sustainable development is always relative to the performance of other potential evolutionary pathways of the industrial network. The method can also be used to evaluate the different evolutionary pathways to an intrinsic value of a sustainability goal, however this requires the performance criteria of

²⁴ Section 4.5.1 discusses the difference between using local and global scales

sustainability to be known *a priori*. It would require a best and worst global value for each of the indicators, representing some external reference point. Such global scales could perhaps be identified in terms of what a network is technically capable of achieving in terms of functionality. How this might be achieved is discussed in more detail in section 4.5.1 and is illustrated in the modeling results in appendix A4.

The second step is to convert the interval scales for the different performance indicators into value scales. This process requires a value judgment about preferences for different levels of indicator performance. These preferences can be linear if the analyst values an increase in performance equally throughout the interval scale. In other words, a value scale for a particular performance indicator is linear if an evolutionary pathway A with a performance indicator of value X is valued twice as good as an evolutionary pathway B with a performance indicator of value X/2. However, assuming that there is a linear relationship between an increase in the performance indicator and an increase in preference, without critical examination, can lead to “extremely misleading and biased results” (Belton and Stewart 2002). Common shapes for value functions are linear, concave, convex, sigmoidal or step-wise. Concave and convex shapes are used when an increase in performance provides, respectively diminishing or increasing returns, while step-wise functions can be used to represent thresholds. The application of value functions to performance scales provides the analyst with a set of value scales, which subsequently can be compared to each other.

The comparison of different values scales requires the elicitation of weightings for each of the value scales. This elicitation of weights is not an easy task, but requires preferential information from the analyst about the relative importance of trade offs between criteria. Besides their numerical value associated with some notion of relative importance, each weight represents also a scaling constant, which makes the different value scales comparable to each other. Thus, the process of selecting weights as a measure of preference is informed by the numerical values assigned to each attribute (which in turn is a function of a value function shape) and has therefore underlying valuation elements associated with them. Several techniques are available to elicit the importance weights for each performance indicator, most notably Swing Weighting

Techniques, Indifference or Trade-off Weighting, Direct Ranking or Ratio Estimation²⁵. The choice for a particular technique depends on the amount of time available to interact with the stakeholders, the character of the criteria (ordinal, cardinal or categorical), the ranges of the different scales and whether it is possible to define preference *a priori* (Basson 2004:3-24). Since the functional and structural performance criteria used here have different scales, and therefore these weightings do not only present relative importance but also scaling constants, it is suggested to use Trade-off Weighting to elicit the weights. Trade-off Weighting explicitly considers the attribute ranges, which reduces potential weight biases.

Each analyst might have different value functions and weightings for each of the structural features, depending on the position of the analyst internally and/or externally to the network, depending on whether the analyst is a single organisation or a group of stakeholders and depending on the analyst 's world view on the potential future in which the network might operate (the context scenarios are discussed in section 3.2.3.). Only through knowing the value functions and weightings explicitly, a sensible notion of trade-offs between the different functional and structural criteria of an industrial network can be attempted. Subsequently, these four different performance scores for efficiency, effectiveness, resilience and adaptiveness can be added up to form an overall score for the structural feature of the industrial network state. The overall score for structural performance also ranges between 0 and 1.

²⁵ These techniques are discussed in great detail in Belton and Stewart (2002).

		Structural components			
Normative components		Efficiency	Effective	Resilience	Adaptive
	Environ-mental	0~1	0~1	0~1	0~1
	Social	0~1	0~1	0~1	0~1
	Economic	0~1	0~1	0~1	0~1

Figure 4- 5 Relating normative performance of sustainable development to the structural features of the system.

The fourth step is to relate the structural performance to the functional performance of the industrial networks. In section 4.4.1, it was argued that the functional performance of industrial networks (in terms of their contribution to sustainable development) can be assessed by normalising the performance of a particular system to the:

1. performance of other network evolutions at that particular point in time, or
2. need for that particular functionality at that particular point in time.

By applying the process of eliciting value functions for the different functional criteria and assigning weights to each of the value scales, an overall index ranging between 0 and 1 can be obtained for the functional performance of an evolutionary pathway.

The two preceding steps result in an aggregate score for the functional performance and the structural performance of the industrial network at a particular point in time for a particular contribution. It can be argued that function and structure are compensatory. In other words, a network with a low functional performance but a high structural performance is equally valued as an industrial network that has a slightly better functional performance and a slightly worse structural performance. However, for both

extremes, a functional performance of 0 or a structural performance of 0, the overall performance of that particular network should be 0. By adding the functional score and the structural score together, an overall score can be obtained that reflect the compensatory nature of both function and structure. However, two thresholds values should be employed to ensure that the overall score is only positive if both functional and structural performances are above a certain performance threshold.

The final step is to relate the different normative criteria of sustainable development to each other. However, like structural indicators, the normative components of industrial networks are often conflicting. Again, preference information about the value functions, or pair-wise preference relationships within an outranking approach, and weightings associated with the different normative criteria is required to provide an overall assessment of sustainable development of industrial network evolutions.

The disadvantage of this exercise is that the evaluation depends a great deal on the different evolutionary pathways that are explored. Each evaluation of sustainable development of industrial networks is relative to other evolutionary pathways that are explored. However, as discussed in chapter 3, there are an unlimited number of potential pathways that an industrial network can take and as such it is impossible to know whether there are other (more attractive) pathways which sit outside the confines limited capacity of any analysis. Chapter 5 discusses this problem in great detail and argues that, by focusing on different 'mental models' as agent scenarios within particular context scenarios, it is possible to explore a sensible set of potential evolutionary pathways. By expanding the analysis over a wider range of potential pathways the evaluation becomes more meaningful.

4.5.1 Evaluating sustainable development on a global scale

The previous section has discussed how sustainable development of different evolutionary pathways of an industrial network can be measured, while taking into consideration the conflicting objectives between some of the structural and functional criteria. The downside of the evaluation of sustainable development using agent-based simulation models is that each performance measurement is relative to the other evolutionary pathways that have been analysed. As such, it is possible to determine

whether an intervention can improve sustainable development of an industrial network evolution, but it is not possible to determine how much more could be possible.

In Beck, Kempener et al. (2008) and Kempener, Beck et al. (in review) a methodology has been developed that combines global dynamic multi-objective optimisation (GDOM) with an ABM approach. Global dynamic multi-objective optimization models (where 'global' refers to optimizing the network in its entirety over the planning cycle) are used to determine preferred industrial network evolution with regards to a range of relevant sustainability criteria over a strategic planning time frame. The GDOM assumes global control, and by definition takes into account only limited consideration of individual agent objectives, instead focusing on what is technologically feasible and preferable in terms of global performance. This approach is consistent with an environment in which, for example, new policy is being proposed for design and management of infrastructure networks. This is explored specifically in terms of the case study of Chapter 6 and an illustration of this approach is provided in appendix A4.

By combining a GDOM with the ABM approach developed in this thesis, it is possible to compare the performance of evolutionary pathways of the industrial network against the "best feasible" outcome for the system from the perspective of the analyst. Figure 4-6 illustrates this approach.

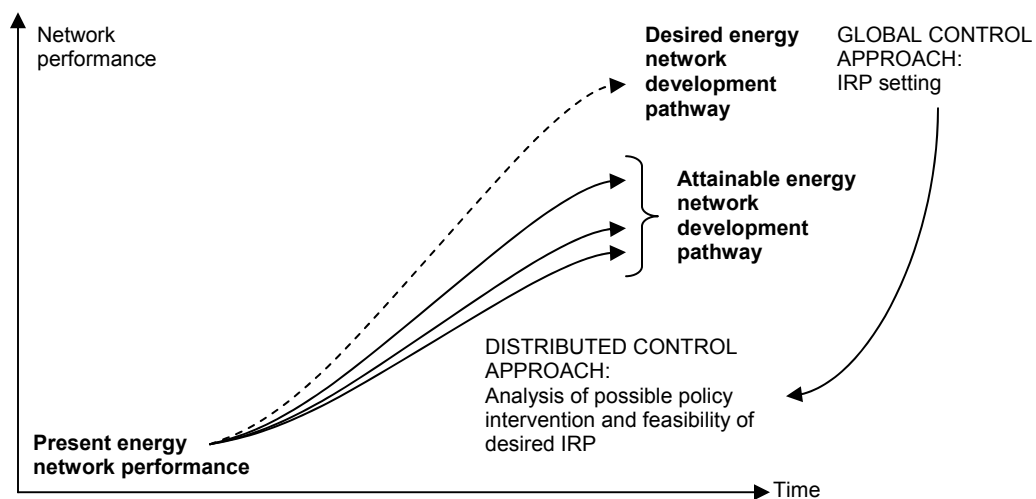


Figure 4- 6 GDOM versus agent-based approaches: The former can determine preferred pathways for resource allocation in the energy network and network evolution.

Distributed control models in turn are suitable to analyze policy interventions and feasibility of attaining the desired optimal goal (Beck, Kempener et al. 2008)

The application of this combined approach of global modelling and distributed modelling is discussed in more detail in two papers (Beck, Kempener et al. 2008; Kempener, Beck et al. in review). The importance of this approach for this thesis, however, is that it illustrates that it is possible to evaluate sustainable development of industrial networks from a global optimum perspective, after which it is possible to explore the consequences of interventions on sustainable development with respect to a normative 'optimum'.

4.6 Conclusions

This chapter has addressed the question of how sustainable development of industrial networks can be evaluated. It recognises that because of the complex characteristics of industrial networks, such an evaluation has to address three challenges:

1. it should recognise that industrial networks are open systems and placed within a larger socio-economic and biophysical system,
2. it should explicitly consider the contribution of an industrial network (in terms of its functionality) as well as those structural features that reflect sustainable development and
3. it should consider the dynamic features of industrial networks with explicit consideration of the value of different evolutionary pathways.

A large number of sustainability frameworks have been evaluated. However, there is no single framework that considers the features of industrial networks simultaneously in a holistic fashion. Therefore, this chapter has argued that adopting a systems approach is necessary to evaluate the contribution of an industrial network to sustainable on the basis of the network's contribution to the larger socio-economic and biophysical system in which it operates. Such contribution is assessed considering four structural features: efficiency, effectiveness, resilience and adaptiveness, using appropriate indicators developed here.

Furthermore, a contribution has been made to the existing discussion on 'resilience', a concept that is increasingly being used to assess sustainable development of industrial networks (especially energy systems). This chapter suggests that a distinction should be

made between resilience as the capacity of industrial network to maintain the provision of a particular contribution to society despite external temporary shocks, and adaptiveness, which is the ability of the system to change towards a different functionality if internal or external parameters change permanently. These permanent changes could be physical (ie there is no need for a particular product or service anymore) or normative (a particular good or service is not wanted anymore, such as asbestos). Finally, this chapter has argued that structural features have to be evaluated throughout the evolution of the system rather than focusing on the end state of the industrial network. This discrete temporal analysis poses significant modelling and analytical challenges, which have been reviewed here.

The final section of this chapter has discussed how different industrial network evolutions can be compared, using MCDA techniques. The application is discussed in more detail in chapter 5, where it is shown how different evolutionary pathways can be differentiated using scenario analysis. Special reference is made to the use of global or local scales for evaluating sustainable development. An evaluation of sustainable development on the basis of local scales compares the performance of different evolutionary pathways to each other. However, the meaning of these performance indicators is limited by the range of evolutionary pathways that are explored. An alternative methodology is to combine agent-based modelling with global dynamic multi-objective optimisation. The application of this combined approach is illustrated in Beck, Kempener et al. (2008) and Kempener, Beck et al. (in review) and provides a tool to evaluate the effects of interventions to the optimal solution from the perspective of the analyst.

Developing interventions to stimulate sustainable development

5.1 Purpose and scope

The purpose of this chapter is to develop a methodology that can be used to assess and develop interventions that stimulate sustainable development of industrial networks. It addresses the question of how future consequences of interventions in real-life can be assessed and explored, using the network models developed in this thesis. Finding an answer to this question is of major practical importance, because it would allow organisations and policy makers to make more informed and (ultimately) better decisions. Simultaneously, it poses the most difficult challenge, because it is impossible to know what the future holds. How is it then possible to use models of industrial networks to assess the consequences of interventions? This chapter will argue that despite the uncertainties²⁶ of the future, the most important driver for industrial network evolutions is organisational behaviour. More specifically, it is the organisational response to uncertainty rather than the uncertainties itself that is the most important determinant of the future. It will argue that, although there will be major disruptions in the future that change the way we live, the evolutionary pathway of industrial networks is shaped by the perception that organisations have about the future rather than the future itself. By

²⁶ The term uncertainty refers to the concept that the future is unknown and therefore cannot be quantified. In the literature, a distinction is made between risk, uncertainty, ignorance and ambiguity, whereby uncertainty is defined in terms of measurable uncertainties. On the other hand, the terms of ambiguity and ignorance are used to describe those situations where both the possible futures are unknown as well as the possible outcomes of any decision. The strategic decisions of organisations in industrial networks described and discussed in this chapter all take place under ambiguity or ignorance, although the term uncertainty is used to describe their perception of the situation.

systematically exploring different perceptions of the future, it is possible to explore a large range of plausible network evolutions. Subsequently, these plausible network evolutions can be used as scenarios within which to develop robust interventions.

The chapter will proceed as follows. Section 5.2 will discuss the use of ‘context scenarios’ and ‘agent scenarios’ for exploring future uncertainty from an analyst’s point of view²⁷. It is argued that by shifting the emphasis from the world views of the analyst as the basis for scenario development to the ‘mental models’ of organisations operating within an industrial network, it is possible to explore the future with more confidence. The second section will discuss the development of scenarios on the basis of mental models of organisations. The final section will discuss how scenario analysis can be used to explore and develop new interventions to stimulate sustainable development of industrial networks.

5.2 Scenario analysis

The three previous chapters have described how an industrial network can be analysed and modelled and how its evolution can be evaluated in terms of sustainable development. Using the analytical framework of chapter 2, the development of non-linear system dynamics multi-scale models in chapter 3 and the methodology of evaluating sustainable development of evolutionary pathways in chapter 4, it is possible to model the complexity of an industrial network, and to assess the consequences of a particular intervention on the sustainable development of the system. However, the question remains whether the model accurately reflects the real-life system, and thus, whether the conclusions of the model are valid for the real-world. Differences between the model and the real-life system are unavoidable, especially over the long-time frames evaluated in this thesis. For example, organisations can change their behaviour in unanticipated ways by, for example, installing a new management board, new inventions can come on the market and change the array of alternatives that are available, and external effects can evolve completely differently to the way it was envisaged at time of model construction. In the context of the bioenergy case study of Chapter 6, for example, oil prices, population growth and electricity prices are all external variables that are impossible to

²⁷ An analyst is defined as the person, or a group of people, interested in stimulating the development of an industrial network. They could be, but are not necessarily, one of the organisations operating within the network.

predict over the next 30 years; however changes in these variables can have important effects on the evolution of the system.

One way of dealing with future uncertainty is by scenario analysis. Scenario analysis can be defined as “focused descriptions of fundamentally different futures presented in a coherent script-like or narrative fashion” (Schoemaker 1993:195). Each scenario presents a different ‘mental model’ of the world, and the purpose of scenario analysis is to envisage futures that are not, or have not been, part of the analyst or decision maker’s mind. In this thesis, the ‘mental models’ of the analyst will be referred to as ‘world views’ to differentiate these from the perceptions of organisations within the network coping with the inherent uncertainty in their decision making. The organisational perceptions are referred to as ‘mental models’, because it involves a number of processes translating and acting upon the opportunities that arise throughout the simulation. Two other methodologies to explore the future are forecasting and backcasting. The starting point for forecasting is recent trends, and its purpose is to explore probabilities; whereas backcasting has as its starting point a desirable future and then plans towards that point (Robert 2000:244; Saritas and Oner 2004). In complex adaptive systems, both forecasting and backcasting have limited capacity to represent the future. Forecasting can only provide limited insights because recent trends are themselves an emergent property and do not reflect the actual processes that drive the system. Similarly, backcasting can only provide limited insights because the achievement of a vision does not depend on the decision maker, but (in large part) on the responses, actions and visions of other organisations in the network.

Scenario analysis can, and often does, involve both forecasting and backcasting principles, however the emphasis and purpose of scenario analysis is different. Firstly, the basis of scenario analysis is the current assumptions about current trends and future events. As such, it is different than forecasting, because its purpose is to explore possibilities rather than probabilities (Ackoff 2006:3). In comparison to backcasting, the basis of scenario analysis is assumptions about future uncertainties rather than a fixed future endpoint. As such, scenario analysis is better suited to explore the inherent future uncertainties of complex adaptive systems such as industrial networks.

Scenario analysis has a long history dating back to the old Greek visions of utopia. However, the use of scenario analysis as a tool to aid decision makers in uncertain situations has only been seen in the last 30 years. The origin of scenario analysis for complex problems originated in the development of systems analysis, and coincided with the development of computer processing capabilities, which allowed for analysing and solving complex problems (Bradfield, Wright et al. 2005:798). More recently, scenario analysis has become an increasingly popular tool for academics and practitioners, which has led to a plethora of different definitions, methodologies and principles. Bradfield, Wright et al. (2005) reviewed a large number of scenario analysis studies and schools of thought and distinguished four different purposes of scenario analysis:

- 1) to make sense,
- 2) to develop strategies,
- 3) to anticipate and
- 4) for adaptive organisational learning (Bradfield, Wright et al. 2005:809).

The purpose of scenario analysis in this thesis is to make (1) sense of a particular problem and (2) to develop strategies to address the problem.

In general, the development of a scenario follows the following steps (Schoemaker 1993:197):

1. The problem is defined in terms of the time frame, scope and important decision variables.
2. Stakeholders and their potential role(s) in the problem are identified.
3. A list of current trends and key future uncertainties is identified, on which basis a set of scenarios is developed.
4. In an iterative process, the different scenarios are assessed on the basis of internal consistency and plausibility and scenarios are eliminated or new scenarios are suggested accordingly.
5. If possible, scenarios can be developed into quantitative models to explore the system interactions and the role of key uncertainties.

The distinction between scenarios and models is complex. On the one hand, the development of a scenario is a function of a 'world view' of the analyst, while on the other hand scenarios themselves can form the basis of a formalised model (Wilkinson

2008)²⁸. Traditionally, scenario analysis takes place from the perspective of a single decision maker or from the perspective of a group of stakeholders holding consensus about a set of appropriate futures. In these situations, the models that result from the scenario analysis are predetermined in that they reflect a set of mental models that is consistent at the start of the analysis.

The use of scenario analysis as it has been used in complex decision making can also be applied to the research question in this thesis. An analyst (as defined previously) interested in stimulating sustainable development of industrial networks can develop a set of 'world views' that reflect different scenarios of the future. For example, the set of scenarios that can be developed in the case of industrial network evolution requires assumptions about the growth of the market and the potential introduction of new technologies into the system. However, the analytical framework and computational models developed in this thesis allow for more insights than can be gained from traditional scenario analysis. Instead of only using the world views of analysts (in this thesis, it is the decision maker who wants to stimulate sustainable development) as the basis for scenario analysis, scenario analysis can be used to explore how the 'mental models' of the organisations that comprise the industrial network affect the evolution and future of the system. This fundamentally different approach is illustrated in figure 5-1. In this agent-based approach towards scenario modelling, it is still important to recognise that the initial model represents different scenarios of the future from the perspective of the analyst. However, the analyst perspective is not the basis for exploring the future. Instead, it is the 'mental models' of the organisations that comprise the system that form the basis for exploring the future.

²⁸ Wilkinson (2008) described the relationship between scenarios and models as a chicken-and-egg problem: scenarios are developed on the basis of models, whereas each model is based on a scenario.

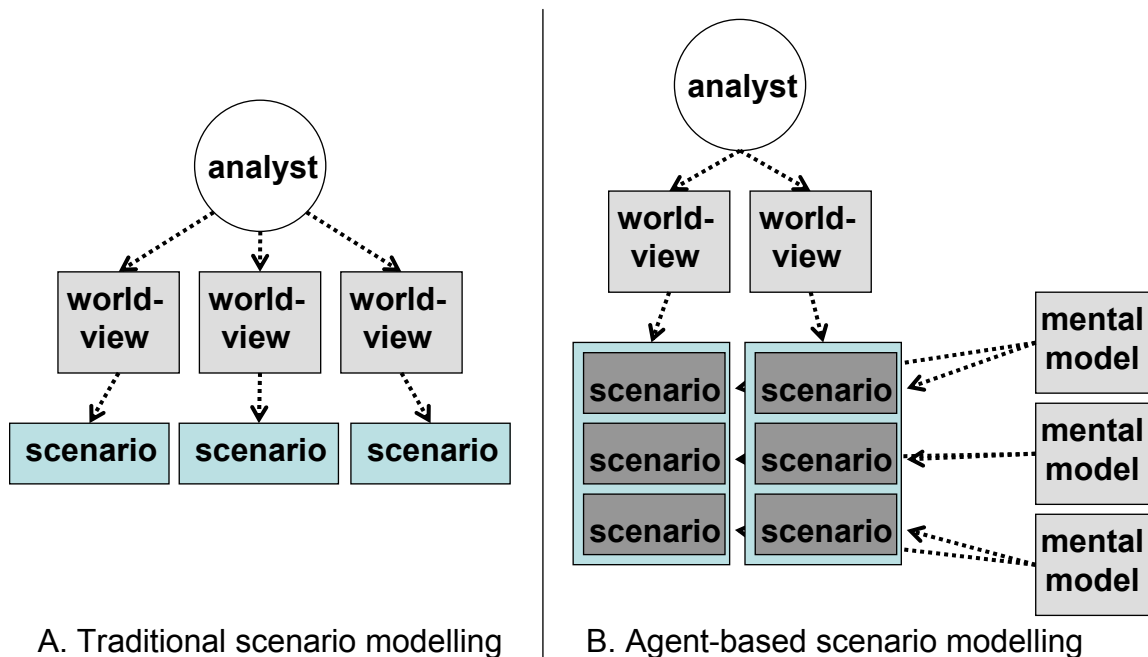


Figure 5- 1The difference between a) traditional scenario modelling and b) agent-based scenario modelling. The traditional approach uses the different wordviews of an analyst as the basis for exploring future uncertainty, while agent-based scenario modelling uses the world views as the context within which the different ‘mental models’ of organisations are used as the basis for exploring future scenario

The use of scenario analysis to reflect the mental models of organisations comprising an industrial network has several advantages. Firstly, it disconnects the presumptions of the analyst from the exploration of the system. For the analysis of complex adaptive systems this is an important advantage, because it allows for an analysis of the system as it is, rather than as it is viewed by the analyst (Shkliarevsky 2007). Secondly, this approach reduces the reliance of accurate data to represent the current state of the system. In traditional scenario modelling exercises, the modelling results are highly dependent on the accuracy of initial input variables, and changes in the initial conditions can have important affects on the modelling outcomes. The use of Monte Carlo analysis to explore the effects of uncertainty in initial conditions can, to a certain extent, accommodate for this sensitivity of model results to data (as employed in Lempert, Groves et al. 2006:527). However, it is impossible to explore all the different initial conditions in large scale systems like industrial networks. With the use of agent-based scenario analysis based on assumptions about the different ‘mental models’ of organisations, the scenario modelling exercise becomes less sensitive to initial data. Instead, it is the perception of organisations about their environment, as expressed in the scenarios, that is the most

important determinant for system evolution. Since these mental models are always a simplification of reality, the sensitivity to initial data is far less in this approach.

Finally, the use of scenario analysis, developed on the basis of different mental models of organisations within the industrial network, reduces the need to assess a large range of different scenarios from the analyst perspective, and increases the robustness of the analysis (Reusser, Hare et al. 2004:6). The analyst him/herself has certain mental models about the context of the industrial network under analysis and how this context might change in the future. In the traditional approach, it is important that these scenarios reflect a large range of fundamentally different futures. However, by using mental models of organisations as scenarios the precise form of these fundamentally different futures is less important, because it is the processes that organisations use to deal with the future that shapes the evolution of systems rather than the pre-conceived perception of the analyst²⁹.

Agent-based scenario analysis requires three steps. Firstly, different mental models of organisations within industrial networks have to be identified. Secondly, these mental models have to be developed into simulation models. Thirdly, these simulation models have to form the basis for scenario analysis. The next section will discuss how different mental models can be distinguished and how they can form the basis for scenario analysis.

5.3 Uncertainty in industrial networks

The agent-based scenario analysis suggested in the previous section requires the development of two sets of scenarios. The first set of scenarios reflects the world view of the analyst (or a group of stakeholders analysing a particular problem). The development of such a set starts with exploring assumptions about current trends and future uncertainties. These assumptions are then combined to develop a set of fundamentally different, but coherent set of context scenarios (Schoemaker 1993:197).

²⁹ As an example, in scenario analysis of industrial systems or energy systems, the future oil price is often an important future uncertainty, which shapes different scenarios. However, for an analyst it is difficult to decide whether the scenarios should reflect a 3, 4 or 5% growth oil prices throughout the analysis. In these situations, changing the oil price from 3 to 4% can often have important implications for the scenario modelling results. By basing scenario analysis on the organisations that comprise in industrial network rather than the analyst, the precise growth shape of the oil prices is not so important anymore. Instead, it is the perception of organisations about whether the oil price is increasing or decreasing that drives the evolution of the system.

The development of scenarios for industrial networks, in particular energy systems, has a long history and dates back to the early 1970s (see for example Chapman 1976).

The second set of scenarios reflects the 'mental models' of organisations that comprise industrial networks and is more of a challenge to develop. Industrial networks consist of a large set of different organisations, each with specific roles. Industrial networks consist of governmental organisations, advocacy groups, competitive buyers and suppliers of goods and services, manufacturers, wholesalers, retailers and customers. Each organisation has different objectives; nor do they share the same assumptions about what variables are important, how current trends will evolve, or what future uncertainties are important to their organisation. In such an environment, it is difficult and almost impossible to develop a set of coherent agent scenarios to which each organisation subscribes.

However, the characteristics that organisations in industrial networks do share is that they all have limited information about what the future holds and limited control about the consequences of their actions. According to Bernstein (1996), the development of industrial networks is intrinsically linked to the management of uncertainty (Bernstein 1996)³⁰. Since only if one acts upon uncertainty, can one create knowledge to pro-actively shape the direction of the future. In other words, Bernstein argues that *the way in which organisations deal with uncertainty is the most important driver for industrial network evolutions*. However, with an increasingly complex and interconnected world, absolute knowledge of a complex system is impossible. Instead, each organisation has to deal with this lack of knowledge in order to come to a conclusion. This lack of knowledge can enter the strategic decision making process in many forms and on different levels. Some information is unknown to the decision maker, either because the information is unattainable or because it is too costly to obtain. Other information is ambiguous, because it is confounded by a large number of other dependent and independent variables (Sterman 2000:23). Furthermore, it may be that the causal relationships of the decision maker are flawed, invalid or restricted, leaving the decision maker in ignorance or in doubt (Walker, Harremoes et al. 2003; Nohria 2006). Finally, the lack of knowledge arises due to the variability inherent to the system under

³⁰ Arcs (1985) argues that not all management functions are connected to risk, so risk management cannot be equated with corporate management. On the other hand, however, uncertainty is more than just risk.

consideration. This variability can be caused by autonomy in human behaviour, the chaotic and unpredictable nature of natural and societal processes (including technological surprises) (Walker, Harremoes et al. 2003:14).

The next two sections discuss in more detail how uncertainty affects strategic behaviour of organisations. Section 5.3.1 discusses the role of uncertainty in strategic decisions in general, while section 5.3.2 discusses how uncertainty affects innovative behaviour of organisations.

5.3.1 Uncertainty in strategic decision making

There are several schools of thought on how to deal with uncertainty in strategic decision making. These different theories range from descriptive to normative, but they all reflect a particular view on how to handle uncertainty. Mintzberg (1999) provides an overview of the different schools of thought based on a two dimensional representation (see figure 5-2 below). The first dimension is related to how an organisation interprets uncertainty in its environment, and the second dimension is related to how it deals with the uncertainty which is inherent to the decision making process. The continuum along each dimension is based on antagonistic views about the different processes that can be used to make decisions, and on the different processes that can be used to view and interpret the external world. The cognitive process reflects different assumptions about how the organisation makes decisions. One the one side of the spectrum there is the “rational” approach, where it is assumed that information should be used to maximise the organisation’s subjective expected utility (SEU); while the ‘natural’ approach assumes that decisions are made ‘on the fly’ in the form of heuristics and routines (Nelson and Winter 1982; Gigerenzer and Goldstein 2000).

The different ways of dealing with uncertainty about consequences are not only reflected in the decision making process, but also in the learning process of organisations (March 1991). The learning process is an essential part of the ‘mental models’ of organisations and needs to be explored in conjunction with the processes that inform strategic decision making.³¹ March argues that, at one end of the spectrum, organisations assume that consequences are a true reflection of their actions, and therefore tend to exploit their competitive advantage. At the other end, there are organisations that view the

³¹ This is illustrated on the basis of the case study in chapter 7.

consequences of their actions as inherently uncertain and therefore adopt explorative methods in learning (March 1991:78). In terms of the uncertainty associated with the external world, some organisations accept the view that the world is comprehensive and controllable, and that strategic choice involves fitting internal strengths to external opportunities; while others adopt the view of an unpredictable and uncontrollable world, and seek to survive through constant learning and the development of cognitive tools to make sense out of continuously changing environmental conditions.

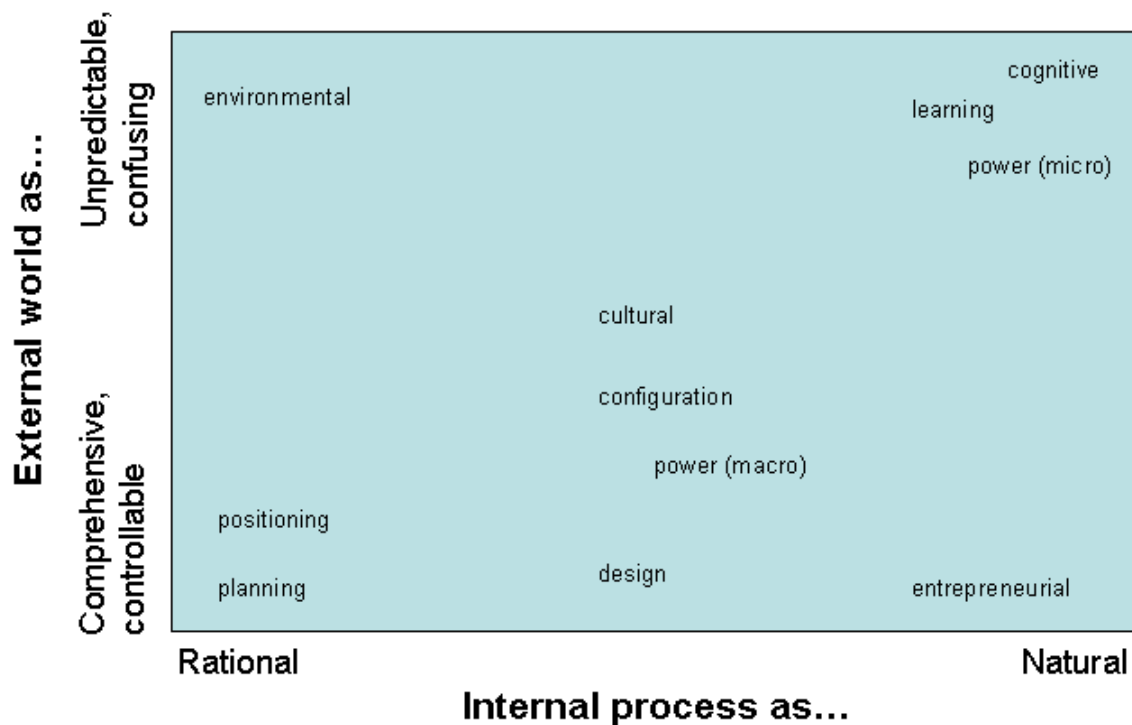


Figure 5- 2 Positioning of several schools of thought for strategic decision making (Mintzberg and Lampel 1999:28)

For example, the environmental school view (or ecological approach) developed by Hannan & Freeman (1977) is that structural inertia, both within the organisation as well as in the environment, limits organisations' capabilities to adapt to environmental changes (Hannan and Freeman 1984:931). Those organisations that have strategies that do not match market conditions have a poorer chance of survival and success. In contrast, the "Austrian" school of strategy points out that organisations constantly have to change and innovate in order to create disequilibrium with market conditions and therefore reduce the effect of competitor's imitations and create new market barriers

(Jacobson 1992:791). Another school, not mentioned as such in figure 5-2, is the strategic choice theory developed by Child (1972). This theory is positioned in between the two schools described above with the view that both organisations, as well as their environment, are dynamic, and that both elements interact in an evolutionary way (Child 1997:44). The evolutionary perspective on strategic decision making is currently portrayed in the cognitive and learning strategy schools.

In principle, each of the schools offers a different perception on how uncertainty affects the decision making process and how uncertainty can be reduced by either representing the world in a particular way or by structuring the decision making process in a particular fashion. As such, these schools of thought represent different 'mental models' for strategic decision making (Sterman 2000). In this thesis, the two dimensions of dealing with uncertainty, either through adopting a particular representation of the world, or by adopting particular decision making process, are used to develop a set of nine different 'mental models' (see figure 5-3 below).

5.3.2 Uncertainty and Innovation

An important aspect of strategic decision making is how it affects the innovative behaviour of organisations. Especially in the context of industrial networks, innovation forms an important process by which the industrial network performance can be changed throughout the evolution of the system. However, like any strategic decision, the decision to innovate is surrounded by large uncertainties. The uncertainties involved in innovative behaviour are so large that Keynes (1938) argued that they required 'animal spirit' rather than calculated decisions involving weighted averages of quantitative benefits multiplied by quantitative probabilities (Keynes 1938:161).

On a more analytical note, Freeman and Soete (1997) distinguish two kinds of uncertainty in the innovation process: technical uncertainty and system-structure or 'market' uncertainty (Freeman and Soete 1997:245). Technical uncertainty is related to the extent to which innovation will satisfy the initial requirements without increased costs of development, production or operation. Freeman and Soete argue that uncertainty in innovation is impossible to measure and can be classified as 'true uncertainty'. System-structure or market uncertainty is related to the extent to which the environment will respond to innovation, so that it provides the benefits expected. Although Freeman and

Soete specifically focus on the economic market as determinant for uncertainty, van de Ven and Garud have extended this perspective by including institutional uncertainty as an important determinant for how and why technological innovations are developed (Ven and Garud 1994:425).

Both kinds of uncertainty reflect the two dimensions of uncertainty that are apparent in any strategic decision making. On the one hand, there is uncertainty about whether the innovation will provide the technical performance criteria it promises to achieve. On the other hand, there is also uncertainty about what the response of the external environment is going to be, and whether the innovation will provide the expected benefits. Like Mintzberg's overview of different strategic decision making schools, Freeman and Soete (1997) discuss a number of strategies that organisations employ with regard to innovation. They argue that rational profit-maximising behaviour cannot explain all the innovative behaviour in industrial networks. In other words, organisations adopt alternative approaches to deal with the inherent uncertainty associated with a) the newness of the technology and b) the possible system-structure response and/or development in the future. These alternative strategies, ranging from offensive, imitative, dependent to opportunistic strategies, can be classified on the basis of the degree to which they recognise uncertainty within their environment (their external world view) and the degree to which they recognise and respond towards uncertainty associated with implementing technologies within the organisation (the degree to which they believe they can assess the consequences of the action) (Freeman and Soete 1997:265). These two processes to cope with technical and system-structured or market uncertainty reflect the dimensions 'internal capabilities' and 'external world views' used to classify strategic behaviour in figure 5-2. This similarity between the role of uncertainty in strategic decisions and innovative decisions more specifically, both very important in terms of shaping industrial network evolutions, provides a common ground for the analysis of industrial network evolutions as a whole.

Innovation does not only involve an organisational decision about in-house research and development expenditure on the development of new technologies, but also reflects the adaptation, diffusion and implementation of new technologies that emerge on the market. The decision to adopt a new technology is as important for innovation as the decision to invent and develop new technologies in the first place. The decision to adopt

a new technology involves two processes: 1) an individual assessment of the innovation's benefit to the adopter and 2) a bandwagon effect of pressure caused by the sheer number of other organisations that have already adopted the innovation (Abrahamson and Rosenkopf 1993:488). In later work, Abrahamson and Rosenkopf have extended the principle of bandwagon effects to include not only the number of organisations as an external effect, but also bandwagon effects on the basis of learning and on the basis of the status of other adopters (Abrahamson and Rosenkopf 1997:292). In other words, depending on the perception of uncertainty in the environment, organisations will use different processes to interpret their environment and act accordingly. In conclusion, this thesis argues that organisational behaviour is affected by organisations' perceptions about technical uncertainty and uncertainty about the consequences of their actions. Depending on their perceptions, organisations will choose a particular process by which to interpret the environment and make decisions and act accordingly.

The next section will discuss in more detail how organisational perceptions about uncertainty can be addressed within simulation models developed to analyse industrial network evolutions.

5.4 Uncertainty and mental models

The previous section has argued that an organisation's perception of uncertainty affects the way in which they make strategic decisions. Firstly, it changes the process by which they view their external world and the cues they extract to interpret their world. Secondly, their perception of uncertainty changes the way in which they attempt to convert information into actions. According to Herbert Simon, this dual side of uncertainty, one cognitive side and one ecological side (Gigerenzer and Goldstein 2000:622), is reflected in the mental models that people and organisations behave: "Human rational behaviour is shaped by a scissors whose two blades are the structure of task environments and the computational capabilities of the actor" (Simon 1990:7). *It is argued here that, by systematically exploring how uncertainty is dealt with in mental models of organisations, it is possible to explore how organisational behaviour affects industrial network evolutions and the potential consequences of interventions to stimulate sustainable development.*

To deal with uncertainty, humans and organisations develop mental models of the world. The term 'mental model' is used in chapter 2 to reflect the totality of factors and processes that assist organisations in their decision making; however there does not exist a clear, specific and mutually agreed definition of mental models in the literature (Doyle and Ford 1998:4). In early models of industrial dynamics, Forrester (1961) recognised the role of mental models in industrial network evolutions and defined them as a substitute for our thinking about the real world (Forrester 1961:49). However both cognitive psychology and the modelling literature suggest a large variety of definitions on what this substitute might be; beliefs, assumptions, images, facts, concepts, abstractions, perceptions and experiences. Despite the plethora of different definitions of mental models, there is a common agreement that mental models consist of two components: 1) cognitive structures that transform information into action, via the decision making process and 2) a mental representation of the world (Doyle and Ford 1998:15; Burns 2000:3; Sterman 2000:28). These two dimensions of the mental model coincide with the two components of uncertainty that organisations face in complex systems (see figure 5-2): the mental representation helps to comprehend environmental uncertainty, while the cognitive processes assist in coping with uncertainty about consequences. These two components of mental models are relatively independent. For example, an organisation can be fairly uncertain about the environment in which it operates and represents the environment accordingly using implicit characteristics, such as social norms and values. However, the decision process of this same organisation can perceive the consequences of its actions as certain and act accordingly. It is argued here that by systematically exploring these two different components of mental models and how they deal with uncertainty, it is possible to develop a set of scenarios that can create an understanding of the direction of industrial network evolutions.

This thesis argues that a set of scenarios can be developed on the basis of organisations' perceptions of uncertainty and their associated mental models. Different processes can be distinguished by which an organisation deals with uncertainty. For the cognitive dimension of mental models, these processes range from full rationality to processes of imitation. For mental representations of the world within mental models, these processes range from using functional characteristics alone to inform decisions, to the use of implicit network characteristics to inform decision making. Combining the two components of mental models with an understanding of different processes to deal with

uncertainty (as per Mintzberg's mapping) provides a two dimensional matrix within which different scenarios can be explored (figure 5-3).

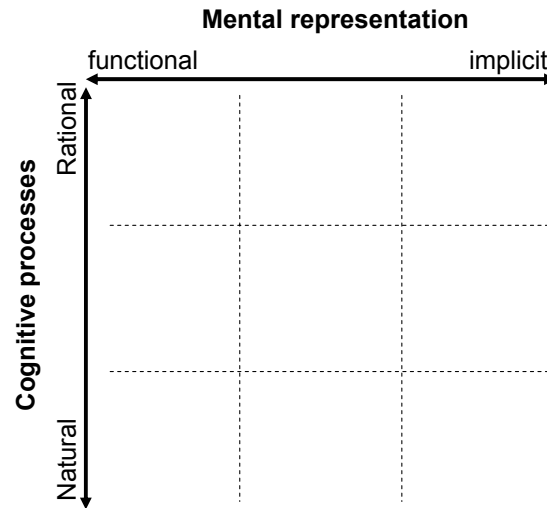


Figure 5- 3 A set of scenarios to represent different mental models of organisations in industrial networks (adapted from Mintzberg and Lampel 1999)

Each 'mental model' is thus a set of 'cognitive processes' and 'mental representations' represented as a distinct different scenario (Jungermann and Thuring 1987:266).

The next step is to represent in more detail the different processes in each of the dimensions and how they can be translated into computational models. Chapter 2 presented an analytical framework to analyse the functional and implicit industrial network characteristics that inform organisational decision making. This framework can be used to explore how different organisational perceptions of uncertainty affect the interpretation of their environment. Figure 5-4 uses the analytical framework to illustrate three ways by which an organisation can extract information from its environment in order to inform its decision making processes.

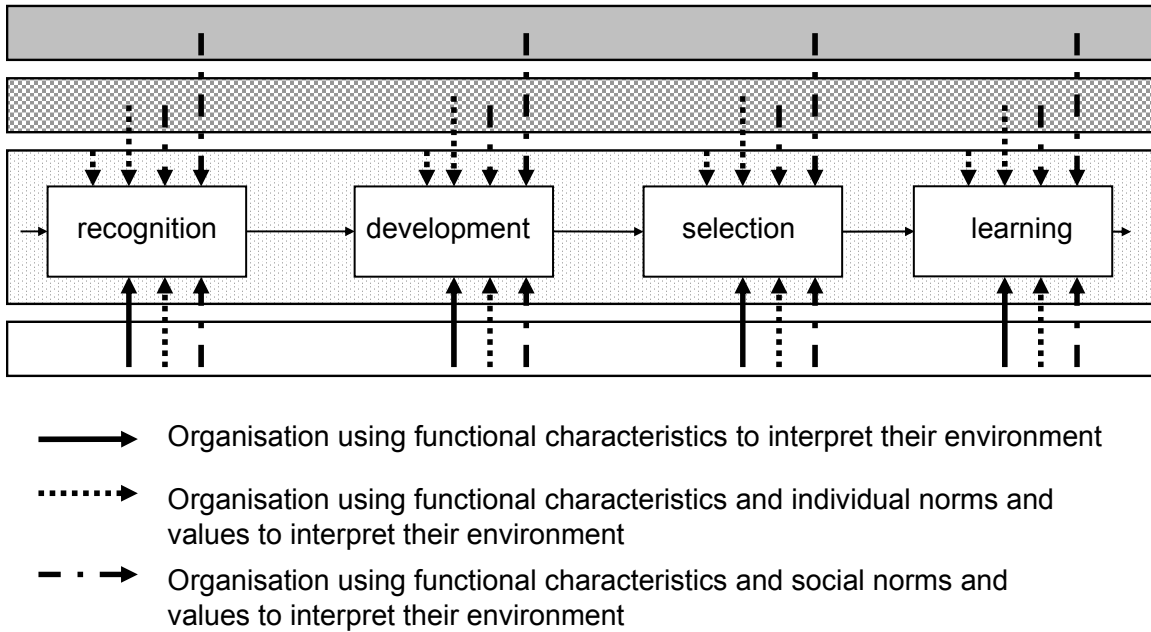


Figure 5- 4 Representing the mental representations in mental models in agent-based simulation models (based on analytical framework of Chapter 2)

An organisation that uses only functional characteristics to interpret its environment perceives the world as certain. For example, in choosing a supplier for resources, such organisation will base its decision purely on the price per unit of resource. On the other hand, an organisation may base its decision for a supplier purely on the basis of the supplier's social status. This is tantamount to perceiving the world as uncertain. Here an organisation relies on implicit network characteristics to inform its decisions.

Similarly, the cognitive (decision making) processes implicit in mental models can be reflected in the simulation models developed in this thesis. Chapter 3 presented a simplified framework to model the decision making processes. By including or excluding some of the processes that play a role in the decision making process, different mental models can be represented within simulation models. Figure 5-5 illustrates the representation of three different mental models.

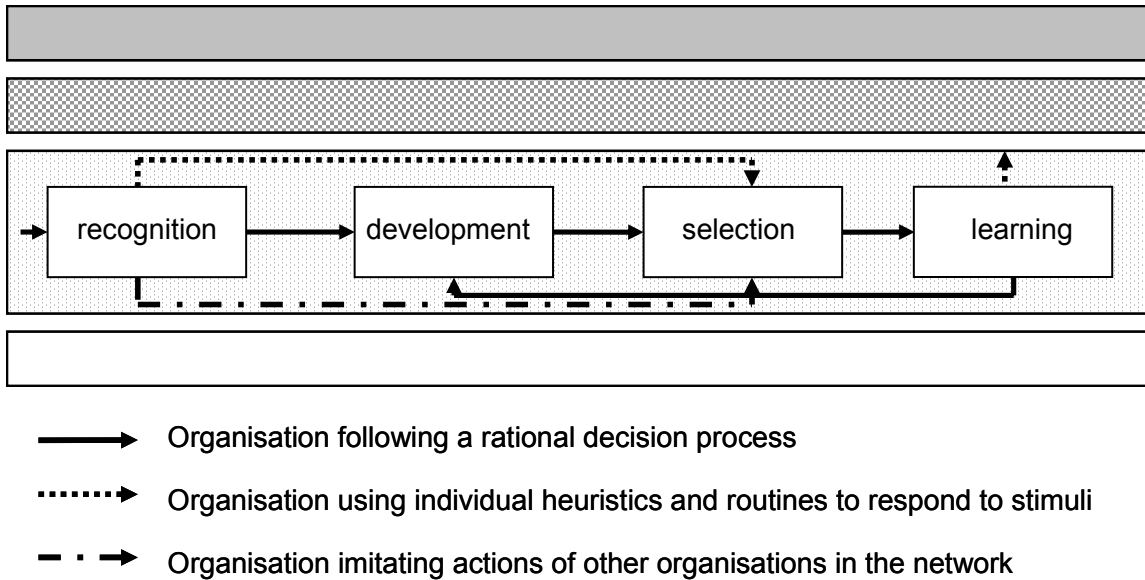


Figure 5- 5 Representing cognitive processes in mental models in agent-based simulation models

The three lines in figure 5-5 illustrate different levels of emphasis on the different sub-processes of decision making. The solid line illustrates a mental model whereby an organisation perceives the consequences of its actions as certain. Under such circumstances, the organisation will evaluate the consequences of all alternatives and select the alternatives that maximises its utility. Furthermore, it will attempt to learn from its consequences by adjusting the alternatives chosen. At the other end, an organisation that is uncertain about the consequences of any alternative will imitate actions of other organisations in the network (dotted line in figure 5-5). These cognitive processes are all placed within the level of individual organisations, because it is within the mental models that these processes take place.

On the basis of the processes described in figure 5-4 and 5-5, it is now possible to develop a set of coherent scenarios for assessing industrial network evolutions. Figure 5-6 illustrates nine scenarios that have been developed in the context of this thesis. These nine are sufficiently disparate as to span the range of possible behaviours and environments with which organisations are faced within their strategic decision making processes. For each dimension of the mental model, three distinct processes have been identified. Each represents a different perspective of an organisation towards uncertainty. Three cognitive processes in mental models are distinguished: 1) rational

behaviour, 2) behaviour on the basis of heuristics and 3) imitation. The three processes linked to perceptions of uncertainty in the mental representation are: 1) the use of purely functional characteristics to inform decision making, 2) the use of individual norms and values as decision criteria, and the use of implicit relational characteristics to choose potential partners and 3) the use of social norms and values as decision criteria as well as the use of social status to choose potential partners.

Generic framework for agent-based scenario analysis

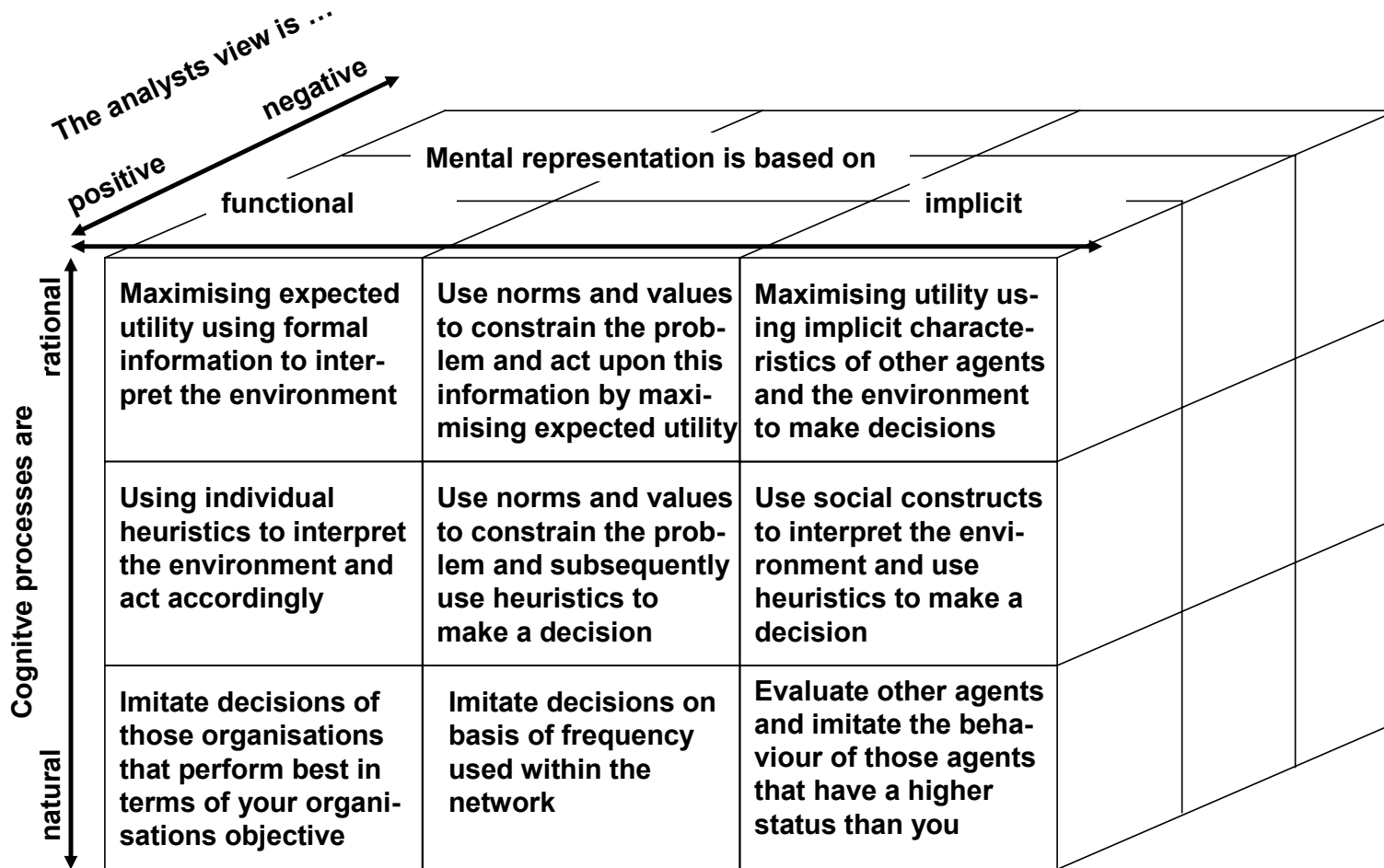


Figure 5- 6 Generic framework for agent-based scenario analysis. The two components of mental representation and cognitive processes are displayed on the horizontal and vertical axes, respectively. The analyst's world view is represented on the third axes.

Since the simulation models of industrial network evolution are based on the interaction of organisations making strategic decisions, these nine distinct scenarios can be used to explore nine different potential evolutions of the network. These nine scenarios can be augmented by others which reflect the decision analyst's own world views about the context within which the industrial network operates will evolve.

5.4.1 Implementation of mental models into scenario analysis

The two components of mental models, the cognitive processes underlying decision making, and the mental representation of world view, can be represented by using different variables³² and processes within the simulation model. The “variables” represent cues of information or alternative actions that can be undertaken, while “processes” represent the judgement and decision rules to evaluate the environment and make decisions. Variables differ between organisations and between different decision situations and are dependent on both actions taken by individual organisations as well as the structure of the environment. Thus, at any time throughout the industrial network evolution that an organisation makes a decision, the variables that represent the decision situation are different. Variables are thus endogenous to industrial network evolution and are not controlled by individual organisations. The judgement and decision rules can be encoded using different rules, and represent the organisation's perceptions towards uncertainty and its associated activities to deal with this uncertainty.

Each ‘mental model’ can be represented as a different scenario by a particular set of rules describing how information is extracted from the environment and by a particular set of rules describing how this information is converted into action. This means that, although the position, actions, level of norms and values and objectives of organisations in the network are different (the parameters for each organisations are uniquely defined at any point in time throughout the model run), they all use the same rules to represent the world and convert that information into action. For example, one scenario that is explored within the case study is the network evolution whereby all industrial organisations, provinces, independent power producers and infrastructure developers base their decisions on current ‘functional’ information (price, efficiency, quality) and in which they attempt to choose those alternatives that maximise their individual utility. In

³² Cognitive psychology describes variables as ‘tokens’, to reflect that as soon as variables enter a mental model they become fixed symbols rather than being capable of assuming alternate values or states (Johnson-Laird 1989 in Doyle and Ford 1998:12).

another scenario, each organisation uses social norms and values to determine the alternatives and they make decisions on the basis of imitation rather than an optimisation strategy. Although in reality, different organisations within a particular network might use different 'mental models', the purpose of the scenario analysis is to explore the range of potential network evolutions rather than to accurately predict a network evolution. From this perspective, the different scenarios are constructed to represent extremes in terms of potential network evolutions. The implementation of different 'mental models' as scenarios is described in detail in chapter 7, in particular section 7.3.

5.5 Scenario analysis for evaluating and developing interventions

So far, this chapter has argued that industrial network evolutions are impossible to predict, but that, by exploring different scenarios, an increased understanding can be created of how industrial networks might evolve. It is argued that the basis for the development of these scenarios should extend beyond the world view of the analyst to include the mental models of organisations that operate within the industrial network under investigation. These organisational mental models are informed by the organisations' perception about uncertainty: uncertainty about the state of their environment and uncertainty about the consequences of their actions. By combining the scenarios of the analyst with the scenarios related to organisational behaviour, agent-based scenario analysis provides a tool to explore the potential future development of industrial networks.

The ultimate aim of this thesis is to evaluate and develop interventions to stimulate sustainable development of industrial networks. In chapter 4, a set of indicators was developed to quantify sustainable development, while goal programming and multi-criteria attribute theory were proposed as means to evaluate conflicting objectives within sustainable development of industrial networks. In this chapter, a set of scenarios has been developed to explore different industrial network evolutions. Both techniques (those of scenario analysis and MCDA) have been used extensively, but largely independently, to explore complex problems and to aid decision makers, especially to issues related to sustainable development (Durbach and Stewart 2003:262). An important reason for this independent application has been that "MCDA aims to resolve

the conflict between objectives, without necessarily giving full consideration to uncertainty in the outcomes, whereas scenario planning provides a model of uncertainty but uses comparatively unsophisticated evaluation techniques to assess the relative performance of alternatives” (Durbach and Stewart 2003:262). On the other hand, both techniques rely heavily on theories about bounded rationality, and how, in uncertain and complex situations, it is impossible to determine the ‘true’ consequences of any action.

Durbach and Stewart (2003)³³ argue that integrating scenario planning and goal programming provides an assessment tool that allows a robust analysis of system performance under different scenarios. The basic idea behind scenario-based goal programming (SBGP) is to formulate a scenario-specific goal program for each scenario, followed by an aggregation over all scenarios. In the context of this thesis, the scenario-specific goal program consists of the list of indicators developed to evaluate sustainable development, while the scenarios represent the different mental models of organisations within an industrial network. Since practical difficulties limit the possibility for an analyst to know what kind of mental models organisations currently use or will use in the next 30 years, a weighted sum of the performance of particular interventions over all the scenarios can be used to cover this uncertainty (as in a hedging strategy). Subsequently, this process can be repeated within different context scenarios.

SBGP starts with the development of an objective hierarchy, whereby the scenarios are incorporated into the objective hierarchy as over-arching criteria whose performance is assessed using a range of sustainable development indicators (as per chapter 4). This is illustrated in figure 5-7. The global evaluation reflects the evaluation of different interventions and how they are able to stimulate sustainable development in different contribution areas (economic, social, environmental) in different performance criteria (both structural and function) under the different scenarios of mental models.

³³ The next paragraphs describing SBGP are discussed in more detail in Durbach and Stewart (2003).

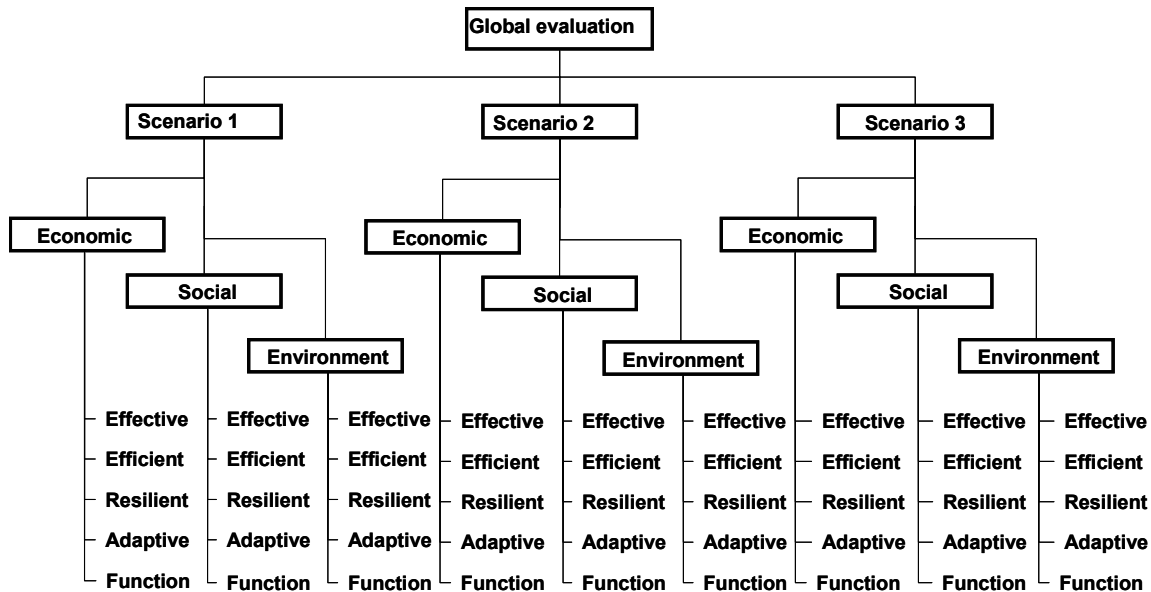


Figure 5- 7 Objective hierarchy for the assessment of sustainable development in industrial networks for 3 of 9 scenarios (adapted from Durbach and Stewart 2003)

The intention of the global evaluation is to determine whether an intervention in an industrial network is more or less robust than other interventions in stimulating sustainable development under different scenarios of ‘mental models’. The context scenario in which the interventions is analysed does not form part of the objective hierarchy, because within each context scenario there might be different stakeholders that are interested in the network evolution and/or the preferences for different industrial network performance criteria within each of the context scenarios might change³⁴. The application of this methodology is discussed and illustrated on the basis of the case study in chapter 7.

Durbach & Stewart (2003) describe the following procedure for the development of SBGP. Each scenario is referred to by the index k within a set of p scenarios (9 in our case). Furthermore, each performance criteria is referred to by the index j within a set of m criteria (15 in our case).

³⁴ Durbach and Stewart (2003) argue that although some stakeholders or performance criteria might become irrelevant in particular scenarios, this could be accommodated for within the SBGP by assigning zero importance weights to those scenarios in which certain criteria are irrelevant (p. 263).

Firstly, two sets of preference information are required for SBGP. Firstly, information about aspiration levels g_{jk} for each of the criteria j in each scenario k are required. By comparing the performance of the intervention against the aspiration level a value of deviation δ_{ijk} can be obtained, whereby a larger score for deviation contributes to a lower score in terms of the overall robustness of the intervention. The aspiration levels do not need to be set *a priori*, but can be determined on the basis of the modelling results. In particular for complex systems, where it is unclear if a particular contribution can be perceived as satisfying, it is probably more appropriate for the aspiration level to be determined on the basis of the simulation results rather than at the start of the analysis. For example, aspiration level g_{jk} representing the aspiration level for efficiency of the environmental contribution in scenario 1 can be set as the highest level of environmental efficiency obtained at that particular time throughout the simulation by any scenario and any of the interventions explored. As such, the consequence of the intervention is explored against the relative contributions of any other interventions explored.

Secondly, preference information on the importance of the criteria needs to be provided by, for example, the use of trade-off or swing weightings methods, denoting the relative importance of a swing between best and worst performance within, and between, each scenario. Thus, each weighting w_{jk} represent a value for a particular criterion within a particular scenario and can be found by multiplying the relative scenario weights Φ_k by the relative criterion weights Ψ_{jk} . The overall score of a particular intervention within a particular scenario can be calculated as follows:

$$\pi_{ik} = \left(\sum_{j=1}^m (w_{jk} \delta_{ijk})^\alpha \right)^{1/\alpha} \quad (5-1)$$

where w_{jk} is the weight applied to the deviation δ_{ijk} of each evaluation from the goal g_{jk} for each criterion j and scenario k , and α denotes the decision maker's philosophy on compensation versus robustness (see the discussion below). The deviation δ_{ijk} can be expressed relative to the aspiration level or it may be constrained to be non-negative, to reflect that once an aspiration level has been achieved, no further improvement is sought. The total performance of an intervention to stimulate sustainable development can subsequently be expressed by:

$$\Pi_i = \left(\sum_{k=1}^p \left(\left(\sum_{j=1}^m (w_{jk} \partial_{ijk})^\alpha \right)^{1/\alpha} \right)^\beta \right)^{1/\beta} \quad (5-2)$$

where α and β are metrics that can represent different preference philosophies reflected in different methods of aggregation (see the discussion below). By exploring interventions under different agent-based scenarios, the total performance Π_i of an intervention can be computed. Subsequently, the most robust interventions can be identified by minimising Π_i . This method is similar to the *regret* method by Savage (1950), which computes the minimal *regret* of a strategy by comparing the difference between the performance of a strategy in some future state of the world to the best-performing strategy in that same future state (Savage 1950 in Lempert, Groves et al. 2006:516).

However, here SBGP is preferred, because it accommodates different decision making contexts and it allows for modelling different decision maker's philosophies by adjusting α and β (Durbach and Stewart 2003:266). An Archimedean norm whereby both α and β equal 1 is more compensatory in that it searches for an answer by assessing the system on its average performance. A Tchebycheff norm of α and β equal to ∞ , on the other hand, is associated with assessments preferring robustness and strong performance over all scenarios and/or criteria. A combination of Archimedean and Tchebycheff is also possible, for example, an assessment that prefers an average criteria performance but robustness from a scenario point of view. (Durlauch & Stewart argue that an Archimedean approach is most applicable for decision situations in which the aspiration levels are clear and trade offs are possible between the system performance and its environmental conditions. The Tchebycheff approach is more appropriate in decision situations that require minimum criteria standards for each criterion within each scenario (Durbach and Stewart 2003:267)).

The SBGP helps analyse the robustness of interventions in stimulating sustainable development in industrial networks, where it is unknown how organisations will respond and drive the evolution of the system. If required, an analyst can carry out the

examination of robustness of interventions on additional scenarios representing his/her own world views on how the context in which the industrial network operates might evolve.

It should be noted that the assessment of sustainable development developed in this section does not provide an exact answer to the question: “Is intervention A more effective in achieving a sustainable industrial network than intervention B?”. Instead, this methodology helps answer the question of whether, under a particular scenario about the future, certain interventions are more robust in stimulating sustainable development than others. Furthermore, the comparison of the different interventions is only relative to the goals set at the outset of the analysis. If these goals are dependent on the performance of other interventions, the outcomes only provide a comparative analysis between the different interventions (which exclude potential interventions that might have performed much better). An alternative approach is to use global dynamic optimisation models (GDOM) to attempt to elicit aspiration levels that represent the best performance possible given the technical and infrastructural capabilities at any point in time throughout the simulation. This would provide an external framework by which it is possible to judge whether the robustness that interventions provide is substantial with respect to the technical capabilities of the system as a whole.

The use of GDOM to provide a reference point for the analysis of industrial network evolution has already been discussed in chapter 4, section 4.5.1. However, it should be mentioned that, although in theory it is possible to develop optimal structural and functional performance criteria for a particular network evolution, these reference points only hold for the particular assumptions that are made within the context scenario. An attempt to develop interventions that stimulate sustainable development for one particular future leaves the system open to vulnerabilities if the future turns out to be different as expected. From this perspective, it might be possible to construct SBGP on the basis of an additional level within the objective hierarchy, representing different context scenarios. On the other hand, this would require stakeholders to determine weights for the relative importance of different context scenarios, a process that might lead to increased cognitive difficulties for the decision makers.

5.6 Conclusions

This chapter has addressed a critical methodological challenge on how to explore the uncertainty associated with development of 'real-world' models, especially if these models attempt to capture complex processes over a long time scale (more than 30 years). It has argued scenario analysis is a valuable approach to explore how the future might unfold and that scenario analysis can provide an increased understanding about the potential consequences of interventions on the future development of industrial networks. However, this chapter has argued that the development of scenarios on the basis of 'world views' of the analyst is insufficient to explore future uncertainties. First of all, the scenarios are based on the mental model of the analyst, which in itself are already simplifications of what the real-world looks like. Secondly, the non-linear and complex processes within industrial networks make that small deviations in initial assumptions can lead to completely different scenario outcomes. The consequence of this is that there is no single set of scenarios that can cover the range of all possible futures that might exist.

The limitations of a traditional scenario analysis approach have prompted the development of agent-based scenario analysis. In this approach, a scenario analysis is conducted on the basis of how organisation operating within the industrial network might employ different 'mental models' to deal with the inherent uncertainty associated with their strategic decision making (including learning) and innovative behaviour. It is argued that the way in which individual and organisations deal with uncertainty is reflected in two separate processes. Firstly, organisations can employ different processes to develop mental representations about the environment in which they operate and secondly, they can employ different cognitive processes to convert these mental representations into action. This chapter argues that by systematically exploring how uncertainty is dealt with within these different 'mental models' of organisations, it is possible to explore how organisational behaviour itself affects industrial network evolutions and the potential consequences of interventions to stimulate sustainable development. In other words, agent-based scenario analysis focuses on how organisations within the network perceive future uncertainty rather than the analyst's perspective of future uncertainty. This method allows exploring a range of different evolutionary pathways that might evolve within a particular context scenario, therefore providing a more rigorous analysis of the uncertainty associated with the simulations

models. Furthermore, it provides the possibility to explore the robustness of interventions within a particular context scenario, taking into consideration the possible responses of organisations towards such interventions.

The final part of this chapter discussed the use of scenario-based goal programming (SBGP) developed by Durbach and Stewart (2003) to quantitatively explore the robustness of interventions to stimulate sustainable development within industrial networks. It also offered a discussion on how this method might be applied within the case study of this thesis. The application is demonstrated in chapter 7.

Case Study: A bioenergy network in South Africa

6.1 Purpose and scope

This chapter describes a case-study of an industrial network in South Africa. The industrial network is located in the province of Kwazulu Natal and is based on biomass as a resource for energy production. The aim of this chapter is to illustrate the complexity of industrial networks, how the analytical framework, the modelling approach and the design methodology developed throughout this thesis can be applied to a real-world application. The models of the cases studies have been developed in several steps, whereby gradually the number of organisations, technologies and externalities impacting on the evolution of the bioenergy networks has been extended. Previous models of the case study have been published in Beck, Kempener et al. (2008) and Kempener, Beck et al. (in review). This chapter will present a comprehensive assessment of the case study, inclusive of those earlier models.

6.2 Background

The case study focuses on the use of bagasse, a biomass waste product from existing sugar industries, for the production of green electricity, biofuels or gel fuel. The potential energy that can be generated from the bagasse is estimated to be around 3031 GWh per year, which exceeds the industries' own requirements of 700 GWh p.a. (DME 2004:5). The case study, and especially its location in South Africa, is an interesting case for several reasons. Firstly, the region has a long history with the conversion of plant biomass into fuels starting in the late 1970s, which makes institutional dynamics the more interesting (Lynd, Blottnitz et al. 2003:499). Secondly, it has potentially one of

the largest amount of (cellulosic) biomass available throughout the world (Marrison and Larson 1996:345; Smeets, Faaij et al. 2007:91). Thirdly, South Africa is keen to pursue small-scale biofuel technology development for rural development as well as large scale production of either electricity or biofuels to fuel the industrial development of the country as a whole. Fourthly, there is a large range of technological options available, each with different consequences for the individual agents and the network performance. The strategic decisions that organisations face are therefore highly uncertain, especially within an evolving policy environment.

A full description of the agents, their functions and the variables that affect their behaviour is described in chapter 7. This section will give a brief overview of the agents involved, their situation and the potential actions they can undertake.

Twelve independent sugar factories have bagasse as a waste product from sugar processing of sugarcane. Bagasse is the fibrous material left over after pressing out the sugar-rich juice, and has a high moisture content of around 50 wt% (Erich, Ohman et al. 2005:569). The South African bagasse has a reported gross calorific value of 7.1 MJ/kg (DME 2004:31). The bagasse is currently burned inefficiently in boilers with a thermal efficiency around 62%³⁵ to fulfil local heat requirements within the plant (Rasul and Rudolph 2000:123). Even when the mill's energy requirements are fulfilled, it is not uncommon to have about 15 – 25% excess bagasse, which in some cases is sold to the pulp and paper industry as an alternative for wood fibre (Kadam 2000:7). The price that sugar mills receive for surplus bagasse is related to its energy value. In South Africa, the price paid for bagasse is around 31.4 ZAR/tonne of bagasse (Mkhize 2005).

The sugar mills have the opportunity to improve their boiler efficiencies and use the excess bagasse to produce green electricity, which is currently sold for 250 ZAR/MWh (DME 2004:71). However, such a strategy would involve substantial investments in an uncertain market. Furthermore, it involves strategic issues such as the choice of technology (bagasse pelletising, combustion versus gasification, liquid fuel versus electricity) and the production capacity. A potential client, competitor or facilitator of the

³⁵ In comparison, standard industrial boilers have efficiencies up to 80% Kadam, K. L. (2000). Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay). Golden, Colorado, National Renewable Energy Laboratory: 1-31.

sugar factories is the existing electricity generator, ESKOM, which has a national commitment to promote renewable energy and is responsible for maintaining and expanding the current generation capacity in South Africa. ESKOM has the possibility to purchase bagasse from the sugar factories to produce its own green electricity in a nearby coal-fired power station³⁶. Furthermore, independent power producers are being encouraged to enter the South African electricity market. These could be potential buyers of bagasse, or competitors for both the sugar mills and the existing electricity generator.

In terms of non-industrial organisations, there are several governmental organisations that have different objectives, such as meeting national environmental targets, supplying cheap electricity to rural areas unserved by the national grid, and providing employment for local workers. More specifically, the Department of Minerals and Energy (DME) is developing policy instruments to open up the electricity industry as well as increasing the percentage of green electricity produced. Furthermore, the Department of Provincial and Local Governments (DPLG) is interested in electrifying rural areas. These governmental organisations affect the evolution of the network in three ways. Firstly, they supply information and (possible) subsidies for different industrial activities. Secondly, the government acts as a regulator developing standards and coordinating markets. Thirdly, the government stimulates the development of the electricity transmission and distribution infrastructure through financial subsidies to local government regions and municipalities, and through the development of electrification plans through industrial partners.

An alternative to the production of electricity from bagasse is the production of bioethanol or bioliquids. These fuels have the advantage that they can be stored and distributed within unelectrified regions in Kwazulu-Natal. Illovo, one of the two major

³⁶ In the last 3 months, the national electrical utility, ESKOM, in trying to deal with rolling blackouts, has issued tenders for combined heat and power generation, targeting just this excess capacity of sugar mills. The price to be paid for such new generation capacity will be determined by a bidding process (obviously linked to any necessary investment in new boiler and turbine plant by sugar mills). The urgency of the current situation, whereby bagasse-fired boiler plant are seen as a relatively quick solution to the generation shortage, might have important implications for technology lock-in effects (the results are discussed in more detail in chapter 7).

sugar companies in Kwazulu-Natal, sums up the following advantages for the production of bioethanol from bagasse:

- health benefits
- safety benefits
- environmental benefits
- social benefits
- foreign exchange benefits with high bioethanol demands in Europe
- development of locally based industries for fuel and stoves (Tomlinson 2004:8).

The last point refers to the use of bioethanol or bioliquids as a local energy source for electricity generation in small-scale generation plants, or as an alternative for paraffin or gas used for cooking and heating purposes (Utria 2004). Bioethanol can also be used as a transport fuel replacing the use of petrol (Salgado 2006; Blottnitz and Curran 2007). Sugar factories could either install these technologies themselves, or independent producers of bioethanol could enter the market.

Figure 6-1 gives a simple overview of the different agents involved and the external factors that impact on the evolution of the industrial network. Using the analysis of chapter 1, the following network structures and characteristics can be identified. Firstly, the case study consists of competitive markets with multiple suppliers and buyers. The 12 sugar mills supply bagasse and there are, depending on the number of independent power producers entering the market, at least three or more potential buyers available. Secondly, the case study consists of several competing supply chains. The electricity supply chain consists of the sugar mills, generators, and transmission and distribution through the local provinces and municipalities. Competing supply chains include the production of ethanol and potentially biogel or the use of bagasse for the production of pulp and paper. There is also the prospect of sugar mills diverting sugar products to fuel in response to decline of global sugar markets. Thirdly, despite the organisations being autonomous, they are dependent on each other for the supply of resources, technology and infrastructure, and co-dependent on local environmental conditions to sustain the availability of bagasse. Decisions made by one organisation affect other organisations in the network, which means that the eventual consequence of each action is a product of the chain of actions and reactions throughout the network. Fourthly, the case study consists of a variety of different agents. Some agents are functional, contributing directly

to the transformation and exchange of resources for energy production. Other agents, such as governmental organisations, affect the network evolution indirectly by providing financial incentives and regulation that changes the behaviour of the functional agents. Government (thus far at least) has been responsible for developing the infrastructure required for the network to function. Finally, the industrial network is affected by developments in other industrial networks and the larger economic system in which it is embedded. Their role is represented by external factors which can change dynamically over time and thus affect the evolution of the overall network.

Translating these network features into the characteristics of complex adaptive systems, it can be argued that the case study displays all of the characteristics mentioned in section 1.4:

- Scarcity of resources: multiple organisations competing over a limited amount of resources available.
- Multiple autonomous decision makers: each organisation has individual objectives to pursue and can enter or leave the network as it desires.
- Learning and adaptation: each organisation has the ability to adapt its strategy or objective depending on its success or failure within the network.
- Background system: the network is affected by developments in other industrial networks and operates within the context of a larger economic system.
- Social embeddedness: organisations are aware of their own actions and those of other organisations within the network. They can communicate and interact with each other and develop institutions throughout time.

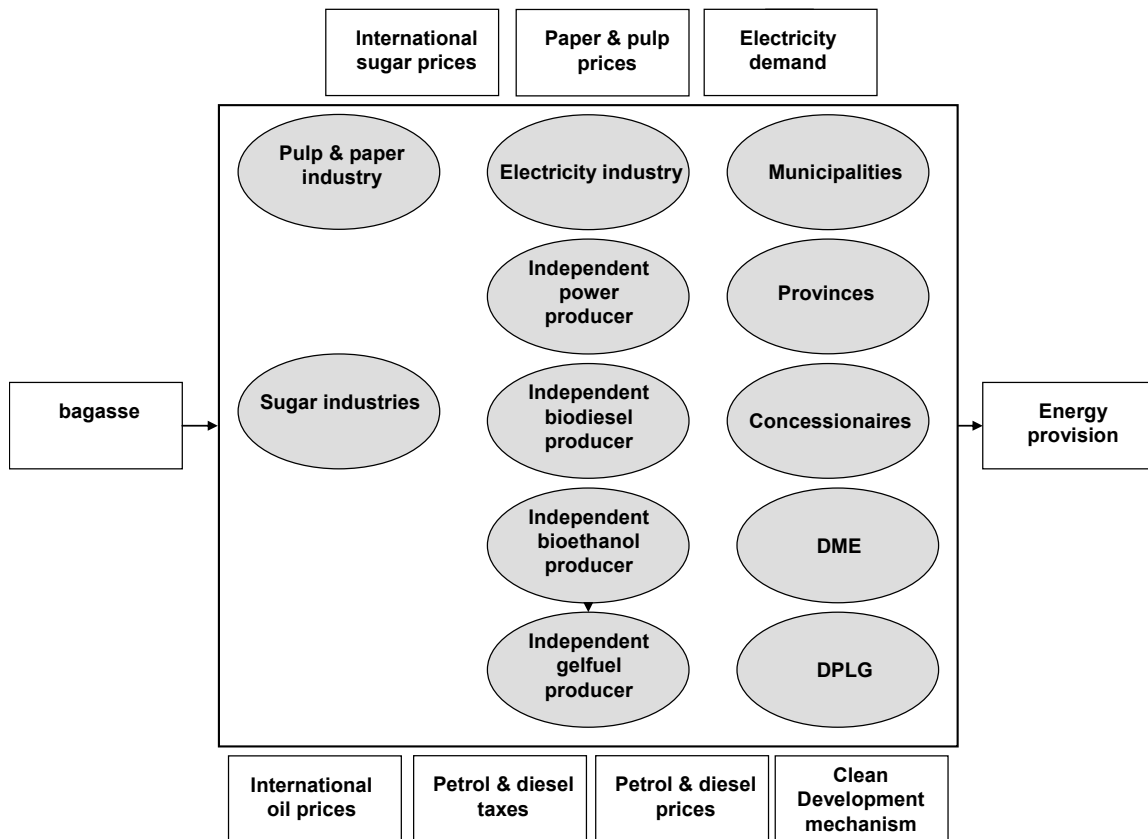


Figure 6- 1 Simplified overview of the bioenergy case study

6.3 A transition towards a bioenergy network

Currently, some sugar industries sell their bagasse for a small price as feedstock to the pulp & paper industry, or they burn it inefficiently to produce steam for process heating. However, there is potential to contribute to rural electrification, cleaner production and social alleviation by using bagasse more efficiently. In this light, transformation towards a more efficient and effective bioenergy network requires the development and implementation of technologies that can convert bagasse into bioenergy. The following technology options exist for the introduction of a biomass energy network in Kwazulu Natal:

- Pelletizing of bagasse
- Combustion of raw/pelletized bagasse for the production of electricity
- Gasification of raw/pelletized bagasse for the production of electricity
- Co-firing of raw/pelletized bagasse in coal-fired power plants
- Physiochemical conversion of raw bagasse into bioethanol

- Biological conversion of raw bagasse into bioethanol
- Storage facilities for bioethanol/bioliquids
- Technologies for decentralised generation of electricity from bioethanol/pyrolysis liquids
- Connections to the grid
- Rural electrification (from grid and non-grid)
- Transport technologies

This list of technologies is reasonably comprehensive, and can be assumed to cover all commercially significant options available to the organisations in the network. Some of these technologies are mature, such as the combustion of bagasse, and have been used extensively in other countries or with similar feedstocks. The operation, maintenance and costs of these technologies are well known. Other technologies have not been implemented on a large scale, except for some demonstration projects. Although they potentially have better performances than traditional technologies, they also bear higher risks and uncertainties. The last technologies in this list are so called 'supportive' technologies, which are required for the practical implementation of a biomass energy network. These supportive technologies consist of road and/or rail transport technologies for bagasse and bioethanol. Furthermore, transmission and distribution networks are required to supply electricity from the location of generation to households and other electricity users.

The agents' decision to invest and implement new technologies depends on their objectives and the circumstances under which they are currently operating. Furthermore, it depends on the decisions of other agents in the network, external factors and other relational and social network characteristics. Finally, the decision depends on the characteristics of the technologies, and the decision making processes used to decide upon their value for the organisation. The following technological characteristics are incorporated into the model to explore their potential take-up within a future biomass energy network:

- feedstock characteristics
- product characteristics
- capital costs

- operational costs
- economies of scale
- energy use
- emissions
- capacity limitations
- efficiency
- production time
- learning curve

Feedstock and product characteristics will determine the applicability of the technologies for the use of either raw, or pelletised bagasse as their energy source. Economic characteristics are well known for the established technologies, such as combustion, but they can have high uncertainty margins for technologies that have not been implemented on a large scale. These uncertainty margins describe the current situation and provide the basis for the (initial) decision making processes of agents. More importantly, it is the decision rules that organisations apply to deal with uncertainty that have a more important effect on the network evolution than the uncertainty in the data itself (see chapter 5 for a more detailed discussion of uncertainty in data availability). Finally, information is provided about learning curves for each technology. The learning curves are, like the economic characteristics, highly uncertain, but provide the agents with information that can be used to analyse the technologies over longer time periods.

An extensive literature study in both academic as well as open source literature has been carried out in order to find data to characterise the technology options available for the introduction of a biomass energy network in Kwazulu-Natal. Since the case study is located in South Africa, all the economic data will be converted to South African Rand (ZAR)³⁷. Appendix A1 provides both overview and detail of the different technologies.

6.4 Model development

In this section, the agent-based model will be discussed using the Overview, Design concepts & Details (ODD) protocol proposed by Grimm et al. (2006). The protocol is proposed by a large variety of different agent-based modellers in order to provide a more

³⁷ FX Converter, www.XE.com, 5 March 2008. 1 US\$ = 7.83 ZAR, 1 EURO = 11.88 ZAR, 1 GBP = 15.49 ZAR.

effective way of communicating the model development and the results. The main aim of the protocol is to improve reproducibility and to provide a common framework to discuss the equations, rules and schemes used in the model (Grimm, Berger et al. 2006:116). Although the protocol is tested for ecology applications, the framework is also applicable for agent-based models in economics, geography, social and political sciences.

The framework consists of three parts. The first part consists of an overview stating the purpose, the state variables, process description and scheduling. The second part discusses the design concepts, which cover how the complex adaptive systems characteristics are represented within the model. The last part gives a detailed description of all the input variables, rules and initialisation. A more detailed description of the model rules representing different mental models can be found in Appendix A3.

6.4.1 Purpose

The purpose of the agent-based model is to explore the effects of the individual decision making processes of agents on the evolution of the bioenergy network in the region of Kwazulu Natal; and to evaluate the economic, environmental and social performance of each potential evolutionary pathway.

The model has been expanded progressively over time in order to create an understanding of the effects of the increasing complexity on the evolution process. Table 6-1 gives an overview of the different models and their content (specified on the basis of agents, technology and network characteristics).

Table 6- 1 Different models and their characteristics

	AGENTS	TECHNOLOGIES	NETWORK	EXTERNAL
Model number	Provinces Concessionaires Independent gelfuel producer Independent ethanol producer Independent biodiesel producer Government Independent power producer Coal-fired power station Sugarindustries	Co-firing Gasification Combustion Burning of bagasse Pelletising Pyrolysis Enzymatic hydrolysis Gelfuel production Fuel engines Transmission infrastructure Distribution infrastructure	Institutional characteristics Relational characteristics Organisational characteristics Functional characteristics	Population growth Transport costs Price elasticity CDM developments Green electricity demand Green electricity price
1a				
1b				
1c				
2a				
2b				
2c				
3a				
3b				
3c				

Although model 3c includes a large number of organisations that potentially can get involved in the development of a bioenergy network in KwaZulu-Natal, there are still a number of organisations, technologies and externalities excluded from the model.

The following potential important organisations are excluded from the model:

- The farmers are currently not modelled as individual decision makers, because most large sugarcane farms are owned by the sugar industries, whose decisions thus mostly affect the availability of bagasse, which is the sole biomass source for the potential bioenergy network.
- Engineering companies and universities are excluded from the model, although their impact on technology development is modelled through learning curves (institutional characteristics of the network).
- Different governmental organisations are amalgamated into one organisation. However, the model allows for the organisation to execute multiple, potentially conflicting, policies, which can represent different governmental departments.

- Municipalities are not modelled as autonomous decision makers. Although their characteristics are retained within the model, they are ruled and governed by decisions made on a local government level. Although this situation most probably will change in the next 30 years, the political process is not included in this model.
- Likewise, households are not modelled as autonomous decision makers, although their characteristics, including population growth, average number of members per household, demographic spread and economic power, inform the energy demand in the region. The households are not modelled as autonomous agents, because currently their demands and wishes are aggregated on a municipal level.

In terms of technology, there are two potential technologies that have not been modelled: acid-based hydrolysis and biomethanol synthesis. The acid-based hydrolysis is excluded from the model, because it has comparable characteristics with enzymatic hydrolysis³⁸. Biomethanol synthesis is excluded on the basis of limited information availability.

There are a large number of external factors that have been excluded from the model, which is inevitable in order to keep the model manageable, whilst retaining its relevance. Most importantly, the international sugar market developments and their potential effects on the decision making process of the sugar industry have been excluded from the model. Changes on the level of the international sugar market can affect the willingness of sugar industries to diversify towards energy production. However, it is assumed here that the sugar prices affect the conversion of sugar products to energy (ie ethanol), while bagasse as a waste stream can be seen as an independent investment opportunity. Furthermore, international and national developments of a gross political nature in Southern Africa can affect the development of a bioenergy network. However, the uncertainty in these factors is beyond modelling within the scope of this thesis.

³⁸ The technical data of the different technologies is described in appendix A2.

6.4.2 State variables and scales

The state variables and scales for the agent-based model is discussed in this section³⁹.

The extended agent-based model consists of the 32 autonomous agents. The following state variables are assigned to each agent:

Table 6- 2 Characterisation of autonomous agents in the agent-based model

Units	State variables	Initial	Processes
12 independent sugar industries located in different regions in Kwazulu Natal	<ul style="list-style-type: none"> • Bagasse availability (both wet & dry)* • Bagasse for own use* • Production capacity* • Costs and efficiency combustion* • Costs and efficiency gasification* • Costs and efficiency pelletising* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction • Relationships • Farmers benefit • Economic, social & environmental weightings in decision making • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • Appendix A2 • 20% • 0 • Appendix A2 • Appendix A2 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years • 0 • 63%⁸ • (1,0,0) • Chapter 7 	<ul style="list-style-type: none"> • Request information • Calculate potential production capacity on basis of available bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Sell green electricity • Update state • Calculate potential bagasse for selling on the market • Evaluate bids and negotiate contract with highest bidder • If declined, negotiate with second highest bidder • Sell bagasse • Update state
1 coal-fired power station located in	<ul style="list-style-type: none"> • Purchased bagasse (both wet & dry)* 	<ul style="list-style-type: none"> • 0 	<ul style="list-style-type: none"> • Request information • Calculate a bid for both wet

³⁹ The asterix refers to those state variables that are used in global dynamic optimisation models of the system as developed by Jessica Beck of the University of Sydney.. The use of global dynamic optimisation to provide goals for technically feasible network evolutions is be discussed in more detail in chapter 4.

Amajuba	<ul style="list-style-type: none"> • Production capacity* • Costs and efficiency cofiring* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction • Relationships • Economic, social & environmental weightings in decision making • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • 0 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years • 0 • (1,0,0) • Chapter 7 	<ul style="list-style-type: none"> and dry bagasse • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Make and execute the purchase decision • Sell green electricity • Update state
1 potential independent power producer located in Durban	<ul style="list-style-type: none"> • Purchased bagasse (both wet & dry)* • Production capacity* • Costs and efficiency combustion* • Costs and efficiency gasification* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction • Relationships • Economic, social & environmental weightings in decision making 	<ul style="list-style-type: none"> • 0 • 0 • Appendix A2 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years • 0 • (1,0,0) 	<ul style="list-style-type: none"> • Request information • Calculate a bid for both wet and dry bagasse • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Make and execute the purchase decision • Sell green electricity • Update state

	<ul style="list-style-type: none"> • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • Chapter 7 	
1 potential independent bioethanol producer located in Durban	<ul style="list-style-type: none"> • Purchased bagasse (both wet & dry)* • Production capacity* • Costs and efficiency hydrolysis* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction • Relationships • Economic, social & environmental weightings in decision making • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • 0 • 0 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years • 0 • (1,0,0) • Chapter 7 	<ul style="list-style-type: none"> • Request information • Calculate a bid for both wet and dry bagasse • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Update state • Evaluate bids and negotiate contracts for bio-ethanol • Sell bioethanol • Update state
1 potential independent bioliquid producer located in Durban	<ul style="list-style-type: none"> • Purchased bagasse (both wet & dry)* • Production capacity* • Costs and efficiency pyrolysis* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction 	<ul style="list-style-type: none"> • 0 • 0 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years 	<ul style="list-style-type: none"> • Request information • Calculate a bid for both wet and dry bagasse • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of

	<ul style="list-style-type: none"> • Relationships • Economic, social & environmental weightings in decision making • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • 0 • (1,0,0) • Chapter 7 	<ul style="list-style-type: none"> investment decision • Make and execute the investment decision • Make and execute the purchase decision • Update state • Evaluate bids and negotiate contracts for bioliquid • Sell bioliquid • Update state
1 gelfuel producer located in Durban	<ul style="list-style-type: none"> • Purchased bioethanol * • Production capacity* • Costs and efficiency gelfuel production* • Profit* • Capital* • Minimum IRR threshold* • Location* • Preferred contract length* • Market share ambitions • Time span for future prediction • Relationships • Economic, social & environmental weightings in decision making • Importance risk, benevolence, conflict, status, past experience, length relationship, trust, loyalty 	<ul style="list-style-type: none"> • 0 • 0 • Appendix A2 • 0 • 0 • 20% • Appendix A2 • 3 years • 100% • 5 years • 0 • (1,0,0) • Chapter 7 	<ul style="list-style-type: none"> • Request information • Calculate a bid for bio-ethanol • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bagasse • Calculate minimum rate of return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Update state
3 concessionaires	<ul style="list-style-type: none"> • Number of municipalities • Subsidies for non-grid connections • Costs for solar power • Purchased bioliquids • Costs for mini-grids 	<ul style="list-style-type: none"> • Appendix A1 • R4500¹ • Appendix A1 • 0 • 6530 	<ul style="list-style-type: none"> • Request information • Calculate a bid for bioliquid • Send bid and negotiate contract length • Calculate potential production capacity on basis of offered bioliquid • Calculate minimum rate of

		R/m ^{2,4}	<ul style="list-style-type: none"> return (IRR) for potential production capacity • Calculate environmental and social performance of investment decision • Make and execute the investment decision • Update state
11 local governments	<ul style="list-style-type: none"> • Number of municipalities • Rural electricity demand (not-electrified) • Price of grid connections • Municipal Infrastructure Grants (MIG) 	<ul style="list-style-type: none"> • Appendix A1 • Appendix A1 • Appendix A2 • Appendix A1 	<ul style="list-style-type: none"> • Evaluate MIG allocation • Calculate least cost connections to the grid within the province • Invest in least-cost grid connections • Update state
1 government	<ul style="list-style-type: none"> • Subsidies for bioethanol • Fuel exemption • Investment subsidies new technologies • Subsidies for green electricity • Subsidies for gelfuel • Subsidies for grid connections • Subsidies for non-grid connections • Policy target for green electricity • Policy target for biofuels • MIG allocation • Electricity Basis Services Support Tariff Policy (EBSST) • Tax rate 	<ul style="list-style-type: none"> • 16.7 c/liter³ • 40% • Appendix A1 • Appendix A1 • 15% • R5438¹ • R4500¹ • 10000 MWh • 4.5% • Appendix A1 • 50 KWh or R48 /month² • 29%¹⁸ 	<ul style="list-style-type: none"> • Evaluate policy targets and network development • Develop policy intervention • Execute policy intervention

Each agent has the potential to establish relationships with other agents in the network. If these relationships involve the transformation of resources (e.g. bagasse, money or information), the following characteristics can be affected:

Table 6- 3 Characterisation of relationships in the agent-based model

Unit	State variables	Initial	Processes
relationship	<ul style="list-style-type: none"> • Contract (start, length, price & quantity) • Trust • Loyalty • Benevolence • Conflicts • Past Experience • Length existing relationship 	<ul style="list-style-type: none"> • False • 0 • 0 • 0 • 0 • 0 • 0 	<ul style="list-style-type: none"> • Calculate Trust • Calculate Loyalty • Calculate loyalty discount

Each local government region consists of several municipalities and each concessionaire has been assigned a finite number of municipalities. The municipalities are not autonomous agents, since they are unable to make autonomous decisions that might affect the evolution of the network. Rather, their electrification rate is a function of the decisions of concessionaries and the local governments, and this, subsequently, is important for the decisions of other agents in the network (e.g. governmental organisations). Their state variables are:

Table 6- 4 Characterisation of municipalities in the agent-based model

Unit	State variables		Processes
municipality	<ul style="list-style-type: none"> • Area • number of households • number of electrified households • population growth • existing high voltage lines 	<ul style="list-style-type: none"> • appendix A1 • appendix A1 • appendix A1 • 1.2%⁵ • Appendix A1 	<ul style="list-style-type: none"> • Calculate number of unelectrified households • Calculate household density

Likewise, households are not modelled as autonomous agents. However, the following characteristics of the households are retained within the model

Table 6- 5 Characterisation of households in the agent-based model

Unit	State variables		Processes
municipality	<ul style="list-style-type: none"> • average household size • electricity use • energy use for cooking 	<ul style="list-style-type: none"> • 5⁶ • 1.42 mwh/yr.hh¹⁷ • 1.67 mwh/yr.hh⁶ 	

There are 8 potential technologies available: pelletising, combustion, gasification, cofiring, pyrolysis, hydrolysis, pelletising and gelfuel production. Their characteristics are:

Table 6- 6 Characterisation of technologies in the agent-based model

Unit	State variables	Initial	Process
Technology: Pelletising, Combustion, Gasification, Cofiring, Hydrolysis, Pyrolysis, Fuel engines, Gelfuel production	<ul style="list-style-type: none"> • Production costs* • Capital costs* • Efficiency* • Production time* • Maximum capacity constraints* • CO₂ production* • Risk perception 	<ul style="list-style-type: none"> • Appendix A2 • Appendix A2 • Appendix A2 • Appendix A2 • Appendix A2 • Appendix A2 • Appendix A2 	<ul style="list-style-type: none"> • Calculate production costs on basis of capacity • Calculate capital costs on basis of capacity • Calculate efficiency on basis of capacity

The environment is characterised by the variables and parameters in table 6-7.

Table 6- 7 Characterisation of the environment in the agent-based model

Unit	State variables	Initial	Processes
Environment	<ul style="list-style-type: none"> • (Dry) bagasse on market* • Price for wet bagasse* • Price for dry bagasse* 	<ul style="list-style-type: none"> • 0 • 31.4⁷ • 0 	<ul style="list-style-type: none"> • Calculate price and demand of green electricity • Calculate price of transport

	<ul style="list-style-type: none"> • Price for green electricity* • Demand for green electricity* • Growth of price & demand in green electricity* • Growth of rural electricity demand* • Price for bioethanol* • Demand for bioethanol* • Growth of petrol consumption* • Price for bioliquids* • Demand for bioliquids* • Price for gelfuels* • Demand for gelfuels* • Transport costs* • CO₂ production from transport* • Growth of population* • Tax rate* • Petrol price* • Petrol tax* • CDM sales value* • History • Institutionalisation 	<ul style="list-style-type: none"> • 250 R/MWh⁸ • 2% • 2.5%⁹ • 2.5%⁹ • 2.5 R/liter¹⁰ • 25.5 m M³/year¹¹ • 4%¹¹ • 3670 R/m³.¹² • 0 • 4.9 R/l¹⁰ • 265000 m³/year¹³ • 0.5 R/tonne.km¹⁴ • 0.14 kg co₂/tonn.km¹⁴ • 1.2%⁵ • 35% • 3.15 R/l¹⁵ • 1.68 R/l¹⁵ • 5 US\$/tonne¹⁶ • 0 • 0 	<ul style="list-style-type: none"> • Calculate CDM sales value • Update market price dry bagasse • Update market price wet bagasse • Update market price bio-ethanol • Update market price bioliquid • Calculate price and demand of gelfuel • Calculate total electricity production • Calculate accumulated CO₂ production • Calculate accumulated social benefit • Calculate accumulated economic performance
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The functional and implicit network characteristics of the industrial network are contained within its history and its institutionalisation. The variables and parameters are shown in table 6-8.

Table 6- 8 Characterisation of history and institutionalisation in the agent-based model

Unit	State variables	Initial	Processes
History	<ul style="list-style-type: none"> • Production history of green electricity 	<ul style="list-style-type: none"> • 0 	<ul style="list-style-type: none"> • Store demand, supply and price for green electricity

	<ul style="list-style-type: none"> • Demand & price history green electricity • Demand & price history bio-ethanol • Demand & price history bioliquids • Demand & price history bioliquids • Price history of wet & dry bagasse • Availability history of bagasse • History of gap between policy targets and actual network performance 	<ul style="list-style-type: none"> • 0 • 0 • 0 • 0 • 0 • 0 • 0 	<ul style="list-style-type: none"> • Store price for wet & dry bagasse • Store availability of bagasse • Store demand and price for bioethanol • Store demand and price for bioliquids • Store demand and price for gelfuel • Store gap between policy targets and network performance
Institutionalisation	<ul style="list-style-type: none"> • Status of agents in network • Largest electricity producer • Largest provider of bagasse • Agent with highest profit • Agent with highest capital 	<ul style="list-style-type: none"> • 0 • 0 • 0 • 0 • 0 	<ul style="list-style-type: none"> • Calculate largest electricity producer • Calculate largest amount of bagasse provided • Calculate highest profit made • Calculate highest capital • Calculate status of agents • Calculate learning experience with particular technologies • Calculate risk perception of technologies

The following resources have been used to initialise the data: ¹(C&V Consulting Engineers 2006); ²(DME 2003); ³(DME 2006); ⁴(Dale, Milborrow et al. 2004); ⁵(Statistics SA 2005); ⁶(Statistics SA 2005; census data); ⁷(Mkhize 2005); ⁸(DME 2004); ⁹Eskom, 1998; ¹⁰(Utria 2004); ¹¹(Coetzee 2006); ¹²(Byrd and Rode 2005); ¹³(Census 2005); ¹⁴(Basson and Petrie 2005); ¹⁶(Spalding-Fecher 2002); ¹⁷(Davidson and Mwakasonda 2004); ¹⁸(Cohen 2007)

Time steps are in quoted in months, since there is monthly variability in the availability of bagasse. The time horizon is 30 years, since most technologies available have a life-

span of around 30 years. The spatial scale of the network is restricted to the region of KwaZulu-Natal.

6.4.3 Process overview and scheduling

In the agent-based model, the agents are autonomous, and have many different behavioural rules depending on their function within the network. Their behavioural rules, as well as the processes that play a role in their environment, (both functional and implicit) are summarised in the previous tables. A full description of the rules can be found in the full model description in appendix A3.

In terms of time scheduling within the models, the agent-based model is timed sequentially, both discrete and continuous. Some processes, such as the production supply and demand of electricity or the development of institutions are continuous, while investment decisions and/or correspondence between the different agents are discrete. In terms of the scheduling of actions, there are three different market settings possible:

- Uncontrolled,
- semi-controlled,
- controlled.

The most common way free markets operate is uncontrolled. The agents can make investment decisions whenever they feel it is appropriate (although as a standard default in this model it is not possible to make more than one investment decision per year). This market setting is the standard mode for running the model. However, if two agents make investment decisions at the same point in time, the actions are scheduled such that the agents with the relative highest bid will act first.

Within each resource exchange, a distinction is made between suppliers and buyers⁴⁰. Negotiations between suppliers and buyers can take place at any point in time. This also means that each buyer can hold multiple contracts with different contract lengths and with different resource quality (eg. bagasse can be supplied either dry or wet, pelletised or unconsolidated). Buyers will contact suppliers if existing contracts for resource delivery come to an end, or if more resources are required. The negotiation is scheduled

⁴⁰ An organisation can be both a supplier and a buyer depending on whether the exchange involves resources or products.

as follows. Firstly, a buyer will send a request for information on the price, quality and quantity of resources that potential suppliers can deliver. On the basis of this information, the buyer will develop a strategic plan for resource acquisition, which includes price, quality and quantity criteria. On the basis of this plan, the buyer will contact potential suppliers by sending formal offers. These offers are examined by the potential suppliers, after which they will either accept, decline or respond with a counter offer. The buyers will examine the suppliers' responses and will make a purchase decision. Figure 6-2 gives a schematic diagram of the scheduling of the negotiation process for an uncontrolled market.

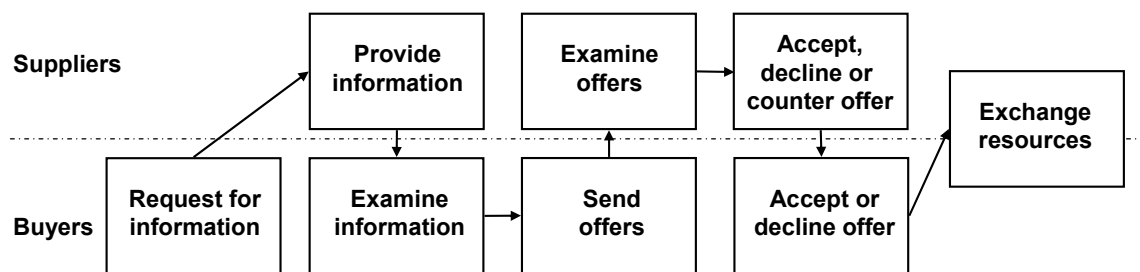


Figure 6- 2 Negotiation between buyers and suppliers in an uncontrolled market

The second market setting is semi-controlled, whereby every agent uses standard contract lengths. This market setting is often encountered in mature markets, where normative and legislative processes have been developed into regulatory standards, such as standard contract lengths. The implication of these market rules is that all agents make investment decisions in the same year. As is the case in the uncontrolled market, the agents with the relative highest bids will act first.

Since all resource exchanges take place simultaneously, the interaction between organisations is scheduled in two rounds. In the first round, buyers will send a request for information to potential suppliers. On the basis of this information, the buyers will determine the criteria for resource acquisition, such as the quantity and quality required, the maximum price that the buyer is willing to pay and the offer. On the basis of this plan, the buyer will contact potential suppliers by sending formal offers. Other competitors that require resources will follow the same procedure. Each supplier will thus end up with a list of offers from different buyers. These offers are examined by the potential suppliers, after which they will either accept, decline or respond with a counter

offer. The buyers will examine the offers and will make preliminary decisions. Some buyers might need to revisit their strategic plans because of a lack of resources, while others have potentially too many resources available to them. Similarly, some suppliers might have resources that they have not sold yet.

Since all resource allocation takes place at one particular point in time, there is a second round scheduled. In the second round, those suppliers that previously declined to offer resources, or had had their offer rejected, have the opportunity to offer their resources to other organisations in the network⁴¹. Subsequently, buyers can examine these offers and either accept or decline. After this round, contracts are set between the suppliers and buyers. Figure 6-3 provides a schematic diagram of the scheduling of the negotiation process for a semi-controlled market.

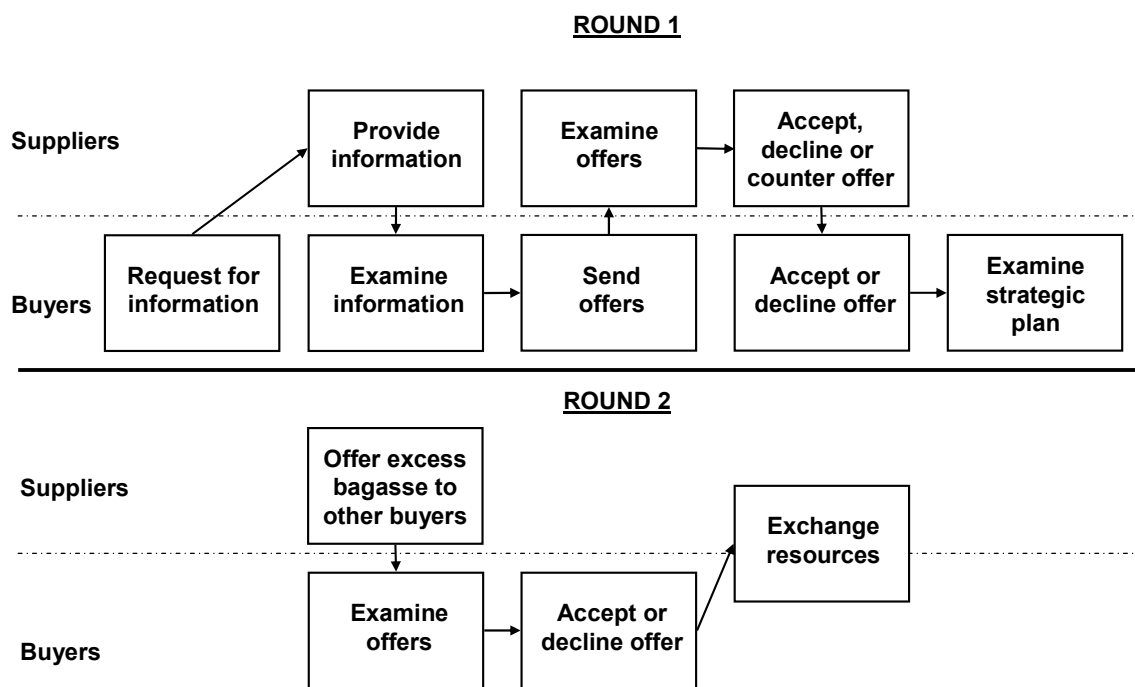


Figure 6- 3 Scheduling of negotiations between suppliers and buyers in a semi-controlled market

The third market setting is controlled in the form of formal auctions, whereby a regulatory mechanism controls the relationship between suppliers and buyers of bagasse in the

⁴¹ Without the second round, situations could occur whereby suppliers have excess and buyers have limited resources for as long as the contract period. In real life, such a situation would be resolved by setting negotiation between the suppliers and buyers. The second round simulates this second round of negotiation.

market. A large number of different auction procedures are possible, such as 'dutch' or 'english' auctions, each with their efficiencies and effectiveness in different market situations. The market setting of auctions is not further explored within this thesis, but is explored elsewhere for a truncated version of this case study (Malan 2006).

6.4.4 Design concepts

The bioenergy case study displays all the characteristics that make it behave like a complex adaptive system. There is resource scarcity and organisations compete with each other for the resources. Organisations behave autonomously and display social embeddedness in order to deal with the complexity of their environment. For example, in those scenarios where social embeddedness has an impact on their decision making they will adapt their risk attitudes towards those technologies that have already been adopted by other organisations in the network. In other scenarios, they can imitate each other meaning that they will adopt the same technology that a better performing organisation or an organisation with a higher status has adopted⁴². Organisations learn and change their behaviour depending on the dynamics in the system; and finally, the system is affected by other networks and larger economic systems.

The way in which these features of the bioenergy case study are modelled and how they result in system characteristics of complex adaptive systems is discussed here. Grimm and Railsback (2005) have developed a list of standard modelling concepts that represent all features of a complex adaptive system. The list can be used as a framework for communication the different features of the model to others. The following concepts are listed:

- Emergence
- Adaptive traits and behaviour
- Fitness
- Prediction
- Interaction
- Sensing
- Stochasticity
- Collectives
- Scheduling

⁴² The exact decision rules within each of the scenarios is discussed in chapter 7.

- Observation

Table 6-9 summarises these, and shows how their description provides deeper insights in the working of the ABM, and reaffirms the value of couching the problem this way.

Table 6- 9 Critical Design Concepts for the bioenergy network

Emergence	Network configuration and performance emerge from the interaction and decisions of the different stakeholder involved; consider external variables (oil prices and CDM certificates) and those variables that emerge through the interaction and behaviour of the industrial agents (e.g. selling prices for bagasse and bioethanol emerge as a function of agent-behaviour and market forces)
Adaptation	Agents adapt their behaviour by imitating the contract conditions of more successful agents within the network; they also use trial-and-error to adjust their internal rate of return thresholds in order to outperform other agents in terms of profitability
Fitness	Relates to the success of an individual to pursue its objectives - industrial agents pursue sustainable economic performance; national government agents pursue objectives such as the existing green electricity target (100000 MWh cumulative) and a biofuel target (4.5% of total transport fuel use) in 2013; regional government pursues rural electrification.
Prediction	Agents linearly extrapolate historic data generated by the model to predict future trends of prices and demand for, and supply of, products. Industrial agents use normative rules based on past experience to predict future risks of potential relationships.
Sensing	Industrial agents are endowed with a notion of whether they are buyers or suppliers in a particular relationship, and they will behave accordingly; they can also obtain information about the historic and current state of the network as a whole.
Interaction	Industrial agents interact through messages. There are five different kinds of messages: information, formal offers, acceptance, decline and withdrawal – all of which contribute to contractual relationships
Stochasticity	Both technical and valuation uncertainties exist – the former relating to parameters such as green electricity price, transport costs, bagasse availability, electricity demand etc (addressed through sensitivity studies and or probabilistic sampling methods); the latter relating to future agent behaviour (addressed through scenarios).
Collectives	Network-wide norms and values are transposed as regulative, normative or cognitive institutions onto the agents within the network.
Observation	Uncertainty analysis used to identify important network variables that impact on network evolution; enables comparison with the optimal network configurations resulting from the GDOM. Comparison can be used to develop instruments that are able to affect agent behaviour to deliver preferred direction for network evolution.

6.4.5 Practical implementation

The model has been implemented using a programme package called AnyLogic™. AnyLogic™ is developed by XJ Technologies and is the first and only dynamic simulation tool that brings together System Dynamics, Discrete Event, and Agent Based modelling approaches within one modelling language and one model development environment (www.xjtek.com). AnyLogic™ is developed on the basis of an object-oriented model design paradigm, the language is based on Java and the models are compatible with the Eclipse framework. AnyLogic™ is an open modelling platform, which means that there are no predefined decision rules within the model. This means that the modeller has the freedom to write any decision rule using Java. AnyLogic™ version 5.3.1 was used for the developing the model in this thesis. The model runs on a simple desktop computer (2GB) with an Intel(R) Pentium (R) M processor 2.00GHz and single model runs take up to 115 seconds. Monte-carlo simulations (up to 100 runs) take less than an hour. The modelling results are exported to Excel in real-time, which means that at any time step (a month in this case) information is available about the different characteristics of the agents within the network as well as the system performance. Excel is used to explore, analyse and present the modelling results.

6.5 Model output

The aim of the bioenergy case study is to explore the contribution that bagasse can make to the region of KwaZulu Natal by converting bagasse into energy. However, the conversion of bagasse into energy sources is not the only model output of interest in the case study. As discussed in chapter 4, sustainable development of industrial network evolution is not only determined by its functionality, but also by structural and dynamic features of the network throughout its evolution.

However, the system performance is not the only model output that valuable from this model analysis. As important are insights into the processes that create the system performance. These processes include the decision making of the individual organisations, as well as the institutional processes that inform these decisions. Throughout any model run, organisations evaluate and interpret their own situation and the changes in the environment around them, on the basis of which they make decisions, act accordingly and exchange information. These processes can take place at any time throughout the model run. Model outputs can create important insights,

regardless of whether they result in actions that affect the system performance or not. For example, some model runs do not result in the creation of a formal bioenergy network, whereby bagasse is exchanged or turned into electricity or biofuels. However, these model runs still provide valuable output, because they show exactly why the organisations decided not to invest or exchange bagasse. By interpreting this information, valuable insights can be gained about what parameters are important in the decision making process, and how these potentially can be manipulated to establish a bioenergy network. All the decision processes form part of the out put of the model and inform our understanding of industrial network evolution.

The output of the decision making and institutionalisation processes, on the basis of the different mental models implemented in the model, is pertinent for creating an understanding of the relationship between strategic behaviour and the emergent patterns within the system.

6.5.1 Environmental considerations

The environmental contribution of the bioenergy network in Kwazulu Natal is measured in terms of the total amount of CO₂ emissions averted by replacing coal-fired electricity with green electricity, by replacing gasoline fuels with bioethanol, by replacing diesel fuels with biodiesel, and by replacing paraffin with biogel.

A bioenergy network in KwaZulu Natal can contribute in several ways to the region itself, and to South Africa in general. First of all, South Africa's power reserve margin has now dropped below internationally acceptable norms, and sits at 5-6%. Demand of electricity is growing faster than expected. Although ESKOM has announced a R350 billion capacity expansion programme, the gap between peak demand and available supply is decreasing (Eskom 2007). Furthermore, there are a number of coal-fired power plants that are close to the end of their life time. The production of electricity on the basis of bagasse could give some relief to the overstretched electricity industry. The contribution will, however, be relative small.

Besides a contribution to the electricity consumption in South Africa, a bioenergy network can also contribute to the renewable energy targets set by the South African Government in 2004. The renewable energy target has been put in place to contribute to

environmental objectives to reduce greenhouse gases. In this perspective, the green electricity generated in the bioenergy network should replace coal-fired electricity. As such, the requirement of the bioenergy network is not necessarily to create as much power as possible, but rather to reduce greenhouse gas emissions in South Africa. From a systems approach, this means that a life cycle perspective should be adopted whereby the total amount of greenhouse gases produced for 1 MWh of electricity or 1 GJ of biofuel, on the basis of bagasse, are compared with the greenhouse gases produced for 1 MWh on the basis of coal or 1 GJ of petrol or diesel. The processes that are taken into consideration from a life cycle perspective are displayed in figure 6-4.

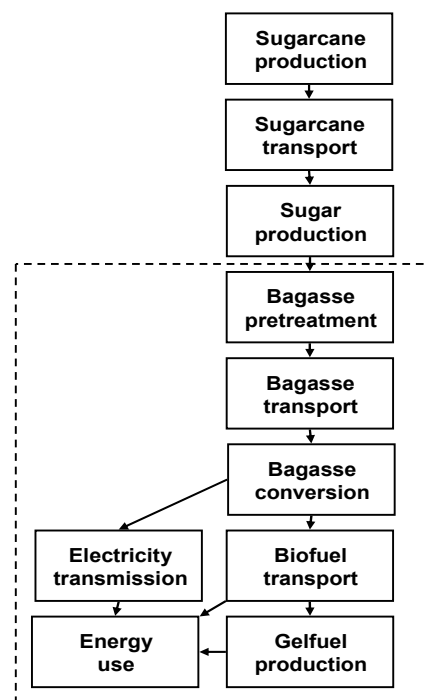


Figure 6- 4 System boundary for life-cycle assessment of emissions in the bioenergy network

Energy use in the production, transport and conversion phase of sugarcane is not attributed to bagasse, since bagasse is a undesired by-product of the production of sugar. All emissions related to sugarcane should therefore be attributed to sugar rather than to bagasse.

The unit of comparison for green electricity is electricity from coal-fired power stations. According to Spalding-Fecher (2002), the average emissions per MWh of electricity

produced by newly planned generation capacity in South Africa is 0.91 tonnes of CO₂/MWh (Spalding-Fecher 2002:81). Since green electricity will replace the need to build new generation capacity, 1 MWh of green electricity delivered to a household saves 0.91 tonnes of CO₂. However, this assumes that green electricity is delivered through the grid, which currently has transmission and distribution losses of up to 20%. If green electricity is delivered through minigrids, distribution losses will fall to only 11% (Spalding-Fecher 2002:80).

The unit of comparison for gelfuel is paraffin, which produces 0.07 kg CO₂/MJ. Biodiesel replaces diesel and bioethanol replaces petrol. Since biodiesel has a lower caloric value than diesel, only 1.37 tonnes of CO₂/m³ is saved, while bioethanol reduces emissions by 2.5 tonnes of CO₂/m³ (IPCC 1996).

Transport emissions are calculated on the basis of South Africa road freight, which has an average emission of 1.7^{e-4} tonnes of CO₂/ton.km (Notten 2001). On the basis of this information, the emissions associated with a ton of wet and dry bagasse, biodiesel or bioethanol are 1.47^{e-3}, 3.05^{e-4}, 2.53^{e-4}, 2.80^{e-4} tonnes of CO₂/ton.km, respectively.

Further details of the energy use in pre-treatment, conversion and processing of bagasse in energy products can be found in appendix A2.

6.5.2 Economic considerations

Several stakeholders are interested in the development of a bioenergy network for economic reasons. The Department of Minerals and Energy (DME) views renewable energy, and biomass-sourced renewables, as an opportunity to attract new businesses to South Africa (DME 2003). Furthermore, the bioenergy network fits into the restructuring of the electricity industry. Such reforms are intended to improve operational efficiency, provide customers with more choice and create opportunities for new financing and markets (Eberhard 2001). Thirdly, the development of a bioenergy network can contribute to the electrification of the KwaZulu Natal region, which allows local business and other entrepreneurs to be established. Furthermore, the network can contribute to local job creation.

The economic benefits that the bioenergy network creates will be measured in the total profits generated in the region, including the subsidies provided and the tax contributions generated. This means that governmental expenditures in terms of investment or price subsidies to encourage new production capacity will be seen as costs to the system, while tax revenues are seen as a revenue. The Municipal Infrastructure Grant (MIG), a yearly grant from the Department of Local and Provincial Planning to the municipalities for rural electrification, is included within the model, but will not be considered as a cost, since expenditures on infrastructure development are independent of the establishment of a bioenergy network.

6.5.3 Social considerations

Since 1994, South Africa has one of the largest electrification programmes in the world aiming to connect households, schools and hospitals to the grid (DME 2001). The programme continued in 2002 as the Integrated National Electrification Programme (INEP) with continuing targets to connect more households. The programme not only focuses on grid connections, but also embodies electricity supply via non-grid technologies, such as Solar Hot Water Systems, hybrid systems or minigrids

Despite these projects, there are still large areas in South Africa that have very low electrification rates. On average, only 60% of the households are connected to any form of electricity service in KwaZulu-Natal (Statistics SA 2005). Furthermore, less than 50% has access to gas or electricity for cooking and heating (Statistics SA 2005). Furthermore, there is still a big difference between households in urban and rural areas. Durban, the biggest city in KwaZulu-Natal, has electrification rates of 80%, while provinces such as Umzinyathi and Umkhanyakude have electrification rates of less than 25% (Statistics SA 2005).

From a social perspective, the bioenergy network can contribute in several ways. Electrification of households contributes to a higher standard of living through poverty alleviation, health benefits and education (Gaunt 2005:1316). Furthermore, electricity allows for more security and access to information sources, such as radio and television (Zomers 2001:55). Furthermore, electrification reduces the chance of fires for households that use candles or lightning for paraffin (Davidson and Mwakasonda 2004:16).

Replacing the use of wood and/or paraffin with gel fuel has several advantages. In 2001 up to 100 000 paraffin related accidents caused fires, burns and deaths through the toxicity of paraffin, the explosive danger of paraffin burners and through indoor pollution and smoke. The use of wood caused patterns of destructive and unsustainable forestry resource exploitation. Furthermore, the use of woodfuels for cooking caused disproportionate health hazards for women and children (Utria 2004). Gel fuel is more effective, much safer and has less pollutants than paraffin or wood (Utria 2004; Visser 2004; Byrd and Rode 2005).

A single indicator is suggested in order to evaluate the social benefits of a bioenergy network. The advantage of a single indicator is that the final evaluation can be based on a triple-bottom line approach consisting of economic, environmental and social benefits. Most decision makers are familiar with such approach.

Electrification and the provision of gel fuel can be seen as independent services, since electricity is used for lightning, radio and television and only a few households use electricity for cooking purposes (Scottish Power 2003:20; Davidson and Mwakasonda 2004:16). If one assumes that the social benefits of supplying gel fuel or electricity are equal, the number of households that are provided with either gel fuel or are electrified can be used for assessing the social benefits of the bioenergy network.

However, the social benefits of electrification are constrained by infrastructure requirements to distribute electricity to the households. Therefore, infrastructure that is developed in regions with low levels of electrification is socially more attractive than the development of mini grid or grid connections in regions with high electrification ratios. Therefore, infrastructure development affects the social, economic and environmental performance of the network.

Gel fuel does not have any constraints in terms of infrastructure, since it can be freely distributed to any household that requires its services. However, those regions that have the highest percentage of households using paraffin, wood or animal dung can benefit more from gel fuel use than those regions where only a limited number of people is using unsafe cooking fuels. The reason for this is that in those regions where a high

percentage of people use unsafe cooking fuels, the stress on the environment (including aspects such as indoor air quality) is higher than that in other regions.

The social performance indicator developed here takes into consideration both localised green electricity delivery, and the gel-fuel delivered to households in a particular region. Each province has been given a separate priority factor normalized on a scale from 0 to 1 using linear value functions to reflect the need for either electricity and/or gelfuel⁴³. The *need* is defined by the number of unelectrified households or the number of household with traditional cooking fuels (wood, animal dung, paraffin) divided by the total number of households in the province. Data is obtained from the national census (Statistics SA 2005).

Table 6- 10 Priority factors for the different localities in the region

Province	Priority factor electrification	Priority factor gelfuel delivery
Ugu	0.65	0.78
Umgungundlovu	0.33	0.51
Uthukela	0.53	0.80
Umzinyathi	0.95	0.95
Amajuba	0.35	0.59
Zululand	0.77	0.85
Umkhanyakude	1	0.93
Uthungulu	0.57	0.66
Ilembe	0.62	0.69
Sisonke	0.84	1
Ethekwini ⁴⁴	0.25	0.31

6.5.4 Efficiency and effectiveness of bioenergy networks

As argued in chapter 4, the functionality of a bioenergy network is not only a function of the end state, but also of the structure of the system and the evolutionary pathway an industrial network undertakes. Furthermore, it was argued that, from a systems perspective, effective and efficient provision of a particular functionality is more sustainable than ineffective and inefficient systems.

⁴³ Whereby 0 reflects full electrification or all households using safe energy sources for cooking.

⁴⁴ Ethekwini locates the largest city within the region.

In chapter 4, the following equation for evaluating the efficiency of a system has been formulated:

$$efficiency_{ind} = \frac{contribution}{resource\ input} \quad (4-1)$$

where the efficiency indicator is determined by the quantity of a particular contribution divided by the quantity of natural resources required to provide that particular functionality.

In terms of environmental functionality of the bioenergy network, quantities are expressed in terms of the tonnes of CO₂ averted. The two variables can be measured as follows. *Contribution* is equal to the total amount of CO₂ emissions averted. *Resource use* is expressed in terms of the total CO₂ content of bagasse use, which as such results in a higher value of efficiency for those networks that consists of highly efficient production facilities in terms of energy conversion.

In terms of economic functionality of the bioenergy network, the quantities are measured in terms of monetary value (ZAR). The two variables can be measured as follows. *Contribution* is equal to the total revenue received from providing green energy products via all industrial organisations involved. *Resource use* is expressed in terms of the value bagasse used within the system. Table 6-11 provides the indicators used to measure the efficiency of the system.

Table 6- 11 Measuring the efficiency of a bioenergy network

	Contribution	Resource Input
Efficiency (economic)	Value of total energy produced (electricity * price electricity + bioethanol * price bioethanol + bioliquid * price bioliquid + biogel * price biogel)	Value of bagasse used in the bioenergy network (value dried bagasse * volume dried bagasse + value wet bagasse * volume wet bagasse)
Efficiency (environmental)	Total CO ₂ emissions averted	Total CO ₂ content bagasse entering bioenergy network
Efficiency (social)	Total GJ of green energy (electricity + gel) provided to rural households	Total GJ of bagasse entering the bioenergy network

In terms of social functionality of the bioenergy network, the quantities are measured in terms of the total GJ delivered to households. The two variables can be measured as follows. *Contribution* is equal to the total number of households that are supplied with electricity plus the total number of households that are supplied with gel fuel. *Resource use* is expressed in terms of the bagasse used, which emphasises the desire for a network that consists of highly efficient production facilities in terms of energy conversion.

For effectiveness the following indicator is used:

$$effectiveness_{ind} = \frac{economic\ value\ contribution}{total\ value\ system} \quad (4-2)$$

where the quality of output and the quality of input are expressed in monetary terms. A discussion on the units of these indicators is provided below.

Both variables are expressed in monetary value to reflect the qualitative aspects of the input and output of the system. The economic contribution is measured on the basis of the profits for all organisations in the network (and tax revenues are seen as part of the economic output of the industrial network). For the environmental contribution, this is expressed in terms of the total CO₂ emissions averted multiplied by the price of carbon, in ZAR/tonne averted. The value of the *social contribution* is expressed in terms of the total delivery of energy sources to households, multiplied by the price of electricity in ZAR/Mwh, or the price of biogel in ZAR/GJ in case of biogel contributions. The *total value of the system* is equal to the capital costs and the subsidies that have been spent to develop the system, including infrastructural developments (but excluding the MIG grant, which is independent from the development of the bioenergy network)⁴⁵. The value of the inputs is equal to the total value of bagasse entering the network, where the value is expressed in terms of the opportunity costs associated with bagasse (the value that could have been obtained if the bagasse was sold to the pulp and paper industry. The specific indicators are shown in table 6-12.

⁴⁵ By using the same expression for *resource costs* for all three functionalities reflects that some system structures are more effective in providing environmental, economic or social benefits.

Table 6- 12 Measuring the effectiveness of a bioenergy network

Effectiveness (economic)	Total profits made by all organisations including tax benefits from government.	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.
Effectiveness (environmental)	Total value of CO ₂ emissions averted (tonnes of CO ₂ averted * value of CO ₂ under CDM)	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.
Effectiveness (social)	Total value of green energy provision calculated by multiplying the quantity of electricity + gel provided to rural households multiplied by price of electricity and gel to households.	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.

6.5.5 Resilience and adaptiveness of bioenergy networks

The resilience and adaptiveness of the bioenergy network are evaluated according to the two indicators developed in chapter 4. For resilience, the following indicator was developed:

$$R_t = \left(\frac{P_t - C_t}{P_t} \right) \cdot \left(\frac{N_t - 1}{N_t} \right) \quad (4-4)$$

where C_t stands for the contribution provided at time t , P_t is the potential contribution that could have been provided if all capacity was used, and N_t is the total number of organisations providing the functionality at time t .

The application of the resilience indicator will be simplified by only taking into consideration the production facilities as a resource for the provision of economic, social and environmental contributions. As such, P_t is measured by evaluating only the different production techniques that are employed within the system, and their potential contributions. For the economic contribution of the system, P_t is calculated by multiplying the generation capacities of the organisations in the network by their efficiencies at full capacity and the price they would receive for their products. In terms of the environmental resilience, P_t is calculated by adding up the potential CO₂ emissions that could be averted if all organisations active in the network would produce green energy. Finally, the resilience of the social contribution is measured by comparing the total

capacity for delivering green energy to households with the actual delivery of green energy to households.

The adaptiveness of the bioenergy network is evaluated using Stirling's indicator for diversity:

$$\Delta = \sum_{ij(i \neq j)} (d_{ij})^\alpha (p_i p_j)^\beta \quad (4-6)$$

whereby p_i and p_j are proportional representations of component i and j and d_{ij} is the difference in attribute between i and j (Stirling 2007:18). α and β will be set at 1.

The proportional representation of each organisation will depend on the context in which the system is evaluated. In terms of the economic contribution, only those organisations that contribute to the economic system will be evaluated (excluding provinces and municipalities) and p will present the profit made by an organisation at the time of the evaluation. For social contribution, only those organisations that contribute to the electrification of the industrial network will be considered, with p reflecting the total number of households electrified. Finally, in the context of the environmental contribution, only those organisations will be evaluated that generate either electricity, biofuels or biogas and their proportional representation p is on the basis of the total GJ produced.

The organisations are differentiated on the basis of three characteristics: their inputs, their processing technology and their output. As such, disparity is expressed in four values ranging between 0 and 1. A disparity value d_{ij} between organisation i and organisation j is 0 if the input resources, the process techniques and the products are all different, 1/3 if one of these three characteristics is similar, 2/3 if two characteristics are similar and 1 if all characteristics are similar.

In conclusion, both resilience and adaptiveness can be expressed in the context of industrial network contribution by evaluating the number of resources, organisations and pathways available within the industrial network. However, there are some important complexities that have not been fully addressed and should be considered explicitly.

Firstly, linear value functions have been used to express both resilience and adaptiveness in order to illustrate the methodology. The results on the basis of this consideration are explored in chapter 7. However, in reality value functions of both resilience and adaptability may not be linear. A high resilience in one year does not compensate for insufficient resilience in another year. Similarly, adaptability needs to be of a certain level at all times in order to label as system as adaptive. However, thresholds for both resilience and adaptiveness have not been developed yet and can be an important focus for further research. Another important issue for the evaluation of resilience and adaptiveness is the context of the industrial network. An industrial network that operates in a certain environment with low levels of uncertainty does not need to be as resilient as a system that operates under high uncertainty. The exact level of resilience and adaptability required depends thus not only on an unknown value function, but also on a subjective judgement about the uncertainty in the environment in which the industrial network operates. It is suggested here that these are important considerations for further research.

6.5.6 Normalisation and weighting

In order to aggregate the functional and structural indicators for sustainable development to each other, two sets of information are required: a) a value function is required that relates the performance score to an interval value scale and b) weightings are required to compare the different performance scores to each other.

The exercise of developing interventions and evaluating interventions according to preferences of stakeholders involved in sustainable development of the bioenergy network in KwaZulu-Natal has not taken place within the context of this thesis. This means that there are no explicit value functions or weightings generated by those stakeholders interested in stimulating sustainable development in Kwazulu-Natal. However, the methodology developed and demonstrated in this thesis allows for stakeholder interaction in the evaluation of the modelling results.

In order to illustrate the methodology, the case study will assume that all value functions are linear and that structural criteria are equally weighted. Furthermore, it assumes that the structural and functional performance of networks are weighted equally. Finally, it will

assume that the normative criteria, ie economic, social and environmental contribution, will be equally weighted from the perspective of the analysis. The consequences of these assumptions are illustrated in the case study results in chapter 7. The interval scales employed for both structural and functional criteria are local. That is, the best and worst value for each criteria are determined by the best and worst value generated by any of the evolutionary pathways that is explored within the agent-based scenario analysis. However, these local scales need to be re-calculated if the analysis takes place under different context scenarios or when additional interventions are explored. Although these simplifications affect the outcome of the modelling results, and their interpretations, they do not impede or restrict the implementation of the methodology in general.

6.6 Conclusions

This chapter has provided a full description of the case study of this thesis: a bioenergy network in the province Kwazulu-Natal in South Africa. The bioenergy network displays all the features of a complex adaptive system. It consists of a large number of autonomous industrial organisations operating in a constrained environment with limited resources. Simultaneously, there are several national and local organisations that have conflicting interests in the development of the bioenergy network, and which affect the network evolution through the introduction of financial support, regulation and targets. Finally, the bioenergy network is located in a region for which not only the economic performance is of importance, but where the bioenergy network could contribute to the environmental and social development of the network. A sustainable bioenergy network is therefore of major importance.

Secondly, this chapter has discussed the implementation of the case study within the modelling framework develop in chapter 2, 3, 4 and 5. Appendix A1 and appendix A2 provide the background to the problem and the data sources that have been used to initialise the models. Without actually running the models, the data gathering exercise and translation of this data into the decision making processes of organisations has in itself already provided an improved understanding of the potential pathways of the industrial network, including how the introduction of new technologies or organisations can take the industrial network in radically different directions. Finally, this chapter has discussed how the different structural indicators developed in chapter 4 can be

operationalised in the context of a bioenergy network. The indicators can also be used for analysis of other bioenergy networks and are therefore an important contribution of this chapter. The following chapter gives a detailed account of modelling insights from the case study, and discusses these in terms of specific methodological features.

Stimulating sustainable development in bioenergy networks

7.1 Purpose and scope

Chapter 6 laid out the details of the case study, how different concepts of complex adaptive systems are encapsulated in the overall model and how indicators for sustainable development are operationalised. This chapter has two purposes. Firstly, it illustrates the applicability and significance of the methodology developed in this thesis to analyse, evaluate and stimulate sustainable development in industrial networks. It shows the implementation of different world views as ‘context scenarios’ and different ‘mental models’ as agent scenarios. Furthermore, it illustrates the application of functional and structural indicators for evaluating sustainable development, and how modelling results can be used to explore robustness of interventions. Secondly, it provides case-study-specific results on how different strategic behaviours of organisations within the bioenergy network, as well as the processes that govern their interaction, affect its evolution. The modelling results discussed in this chapter are based on the most complete version of the agent-based model developed of the bioenergy network in KwaZulu-Natal. However, many insights have been gained from previous versions of the model. The results of previous versions have been presented at several conferences and their insights have been used to develop the methodology presented in this thesis. (Kempener, Basson et al. 2006; Kempener, Cohen et al. 2006; Kempener, Cohen et al. 2006; Petrie, Basson et al. 2006; Kempener, Beck et al. 2007; Kempener,

Cohen et al. 2007; Petrie, Kempener et al. 2008). The results of previous models are not discussed in this chapter, but are illustrated in appendix A4.

This chapter consists of five sections. Firstly, the implementation of the agent-based scenario analysis will be discussed, and how different mental models are operationalised within strategic decision making processes of organisations in the bioenergy network. Subsequently, the modelling results will be discussed. In section 7.3, the effect of different mental models on the performance and evolution of the bioenergy network will be discussed. Nine different scenarios are explored, and the results are used to demonstrate how agent-based scenario analysis can be used to analyse the complex processes in industrial network evolutions. In section 7.4 and 7.5, different interventions are explored and their impact on the network evolution. In section 7.4, two different methods for strategic decision making are introduced, each reflecting a different philosophy of incorporating sustainability aspects into individual decision making of organisations. These two methods are Multi Attribute Utility Theory (MAUT) and outranking (ELECTRE III). In section 7.5, governmental interventions will be explored and compared to each other. The governmental interventions will consist of different financial incentives, different methods for introducing these environmental incentives and different ways of setting governmental targets. Section 7.6 will conclude this chapter with some overall findings on the robustness of interventions to stimulate sustainable development.

7.2 Operationalisation of agent-based scenario analysis

This section discusses how strategic decision making processes and mental models are structured into scenarios that can be used to explore different evolutionary pathways of industrial networks. Much of this relies on informed judgment on the part of the modeller. Of interest here are the logic diagrams (7.2.1), the development of scenarios on the basis of 'mental models' consisting of different combinations of 'rules or heuristics' for 'mental representations' and 'cognitive processes' (recall section 5.4) in 7.2.2 and the operationalisation of these different cognitive processes and mental representation in the case study of the bioenergy network in 7.2.3.

7.2.1 Logic diagrams of organisations

In section 6.2 five different categories of organisations were distinguished that operate within the bioenergy network in Kwazulu-Natal: 1) the sugar mills, 2) independent power, biofuel or biogel producers, 3) concessionaires, 4) regions and local municipalities and 5) the government. Each of these categories of organisations has different alternatives and motives for operating within the network. For example, the sugar industries produce and own the bagasse and can decide whether they process, use or sell bagasse. Independent producers are already established or can enter the network to use the bagasse for centralised electricity, bioethanol, biodiesel or biogel production. Concessionaires have the opportunity to place solar power systems or mini grids in the region for electrifying households. Local government regions receive a yearly electrification budget and need to decide where and how to use it for electrification. Finally, national government can attempt to influence the evolution of the bioenergy network through policy interventions. The logic diagrams for decision processes used by each category of organisations are presented in the next five figures.

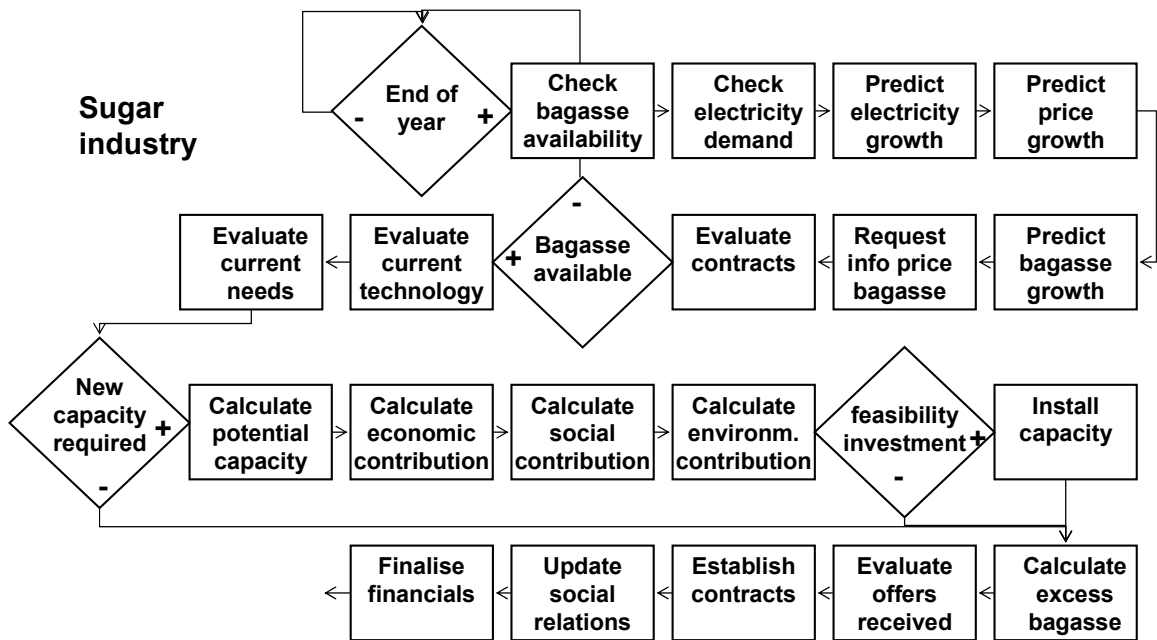


Figure 7- 1 Logic diagram for the sugar industry companies

Figure 7-1 illustrates the most important steps of the decision making process of the sugar industry. Within each of the blocks, there are many rules that inform the outcome of the decision making process. For example, the prediction of electricity growth requires

a set of rules extrapolating historical information into the future. This information is subsequently used to inform investment decisions, including decisions about expansions of existing capacity. Not all information generated in this logic diagram is used necessarily. For example, an organisation that only considers economic consequences of its actions will not use information relating to environmental and social consequences of their decisions.

The mental models are an integral part of the logic diagram, and play a role in two stages in the decision making process: (1) evaluating the feasibility of investments and 2) bid offers and establishing contracts. Together, these two decision processes reflect prospects for an organisation to intervene strategically within the network, and help unravel the consequences for the evolution of the network as a whole. The feasibility study of possible investments helps determine transformation processes that will take place within the organisation; whilst the decision around potential suppliers and buyers affects interrelationships between organisations, and therefore the system structure.

Various technology investment decisions are possible: converting bagasse into electricity (combustion and gasification)⁴⁶, and whether to dry and pelletise bagasse. These impact the logic diagram directly. If the sugar mill has invested in a pelletiser, it follows logically that the mill will evaluate use of dried bagasse rather than wet bagasse in its strategic decision making process.

The decision logic for the existing electricity generator and independent energy producers (either green electricity or biofuels like bioethanol, biodiesel and biogel) are rather similar. All these organisations need to secure bagasse before they are able to consider production of green energy. A second important determinant of their decision making is their location. The logistics of transporting wet bagasse are informed by its low bulk density and high moisture content. A major determinant in an organisation's willingness to invest depends on the location of the resources and whether the sugar mills decide to pelletise the resource. On the other hand, the sugar mills will not be willing to pelletise if there is no secure market for dried bagasse.

⁴⁶ The possibility that sugar mills invest in hydrolysis or pyrolysis technologies is not considered in this model. The reason is that sugar mills will use molasses rather than bagasse to produce biofuels, because that technology is a logical extension of their current business practices; and pyrolysis was viewed as a less mature technology than the others considered here.

This tension between demand and supply of new products reflects many market situations in industrial networks. Often market opportunities arise because organisations see value one organisations offers a particular value for resources, unrecognised by other organisations. However, as soon as such value is created from such resource, organisations offering such resources have to reconsider their operations, because they are suddenly producing something with value. This interaction between individual decisions and the larger, emergent effects within their external environment is a key feature of many industrial networks. The methodology developed in this thesis explicitly captures these complexities (see 7.3.2.1). In the case of the bioenergy network, the value of bagasse is determined by organisations operating within an external to the network. They communicate with each other requesting information about how much pelletised bagasse would cost if it was available, and how much independent power producers would consider paying for dried bagasse. This interaction is an important feature of the agent-based model.

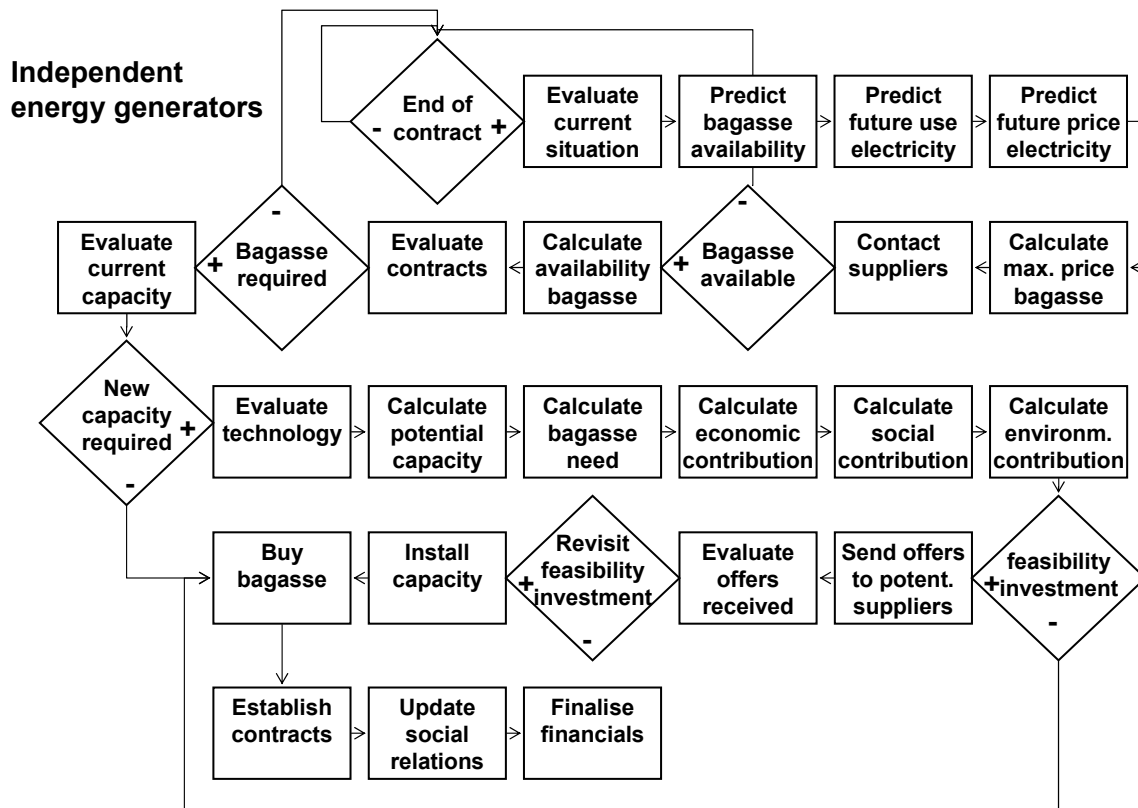


Figure 7- 2 Logic diagram for independent energy producers

Figure 7-2 shows the logic diagram for independent energy producers, for producing green electricity on the basis of bagasse⁴⁷. The same logic structure is implemented for organisations that use bagasse for production of biofuels, or bioethanol for the production of biogel. Again, the feasibility of investments and evaluation of potential suppliers are two important steps in the decision making process, the consequences of which determine the way in which the industrial network evolves.

The third category of organisations in the network is the concessionaires (the three concessionaires are EdF, ESKOM/SHELL and NUON). Each concessionaire is assigned a large number of municipalities within which they have the opportunity to develop electrification infrastructure. Concessionaires are thus not necessarily interested in the production of green energy, but operate in the region of KwaZulu-Natal to provide rural households with electricity. The two alternatives they have is the provision of electricity through solar systems or through the development of minigrids (Spalding-Fecher 2002; Scottish Power 2003). These minigrids can produce electricity by remote engines driven by fuel, while solar systems are installed for individual households.

⁴⁷ Until now, the SA government has failed to attract new investments into the electricity generation sector, largely as a result of the (artificially) low generating costs of ESKOM.

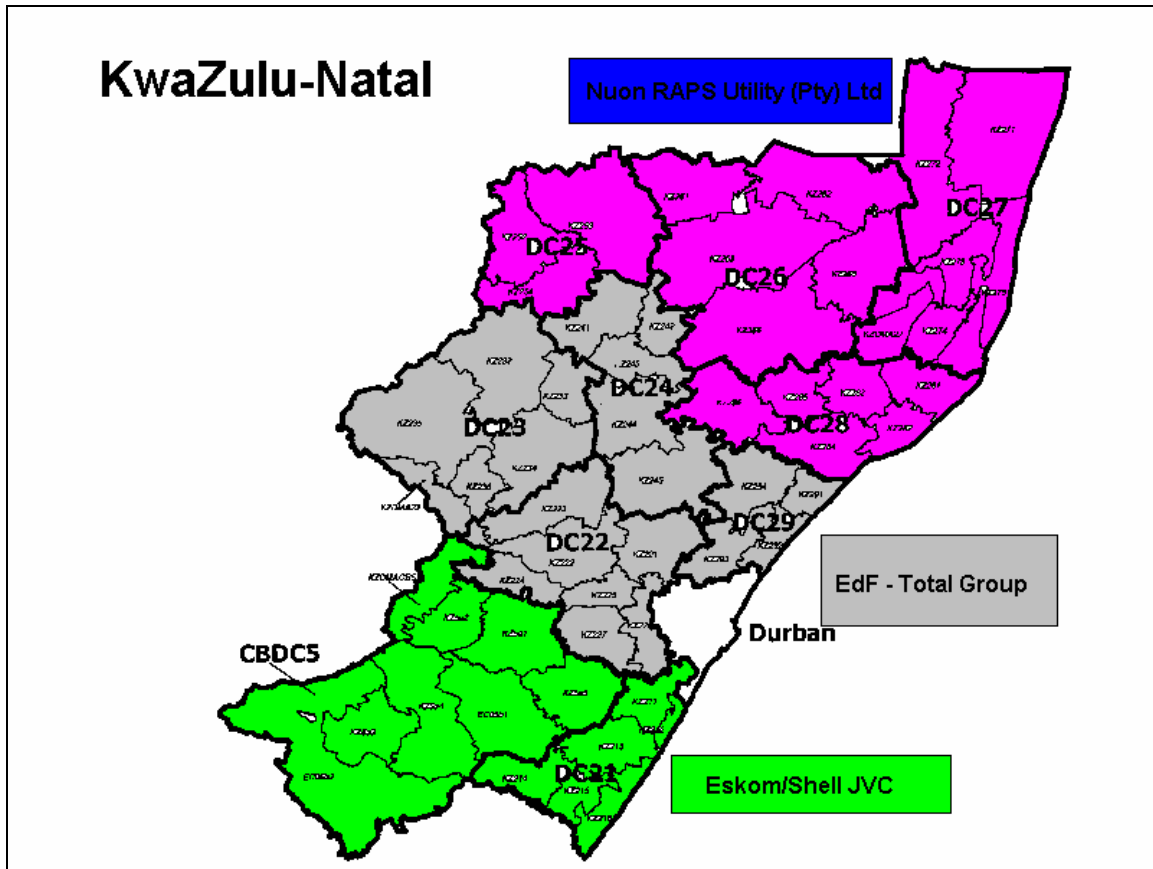


Figure 7- 3 Municipalities and their concessionaires in KwaZulu-Natal (DME 2001:33)

Although concessionaires do not have a direct impact on the bioenergy network, their activities affect the network in two ways. On the one hand, installation of solar systems diminishes the need for electrification on the basis of bioenergy. On the other hand, development of minigrids on the basis of fuel engines could provide an opportunity for the bioenergy network to deliver biodiesel. These are important interdependencies that need to be considered for evaluating the overall evolutionary pathway of the bioenergy network. In the logic diagram, presented in figure 7-4, the step that considers the feasibility of potential projects is the most important activity impacting the network evolution. It is this stage of the logic diagram where different combinations of 'mental representations' and 'cognitive processes' impact on the decision outcome, and therefore the network evolution.

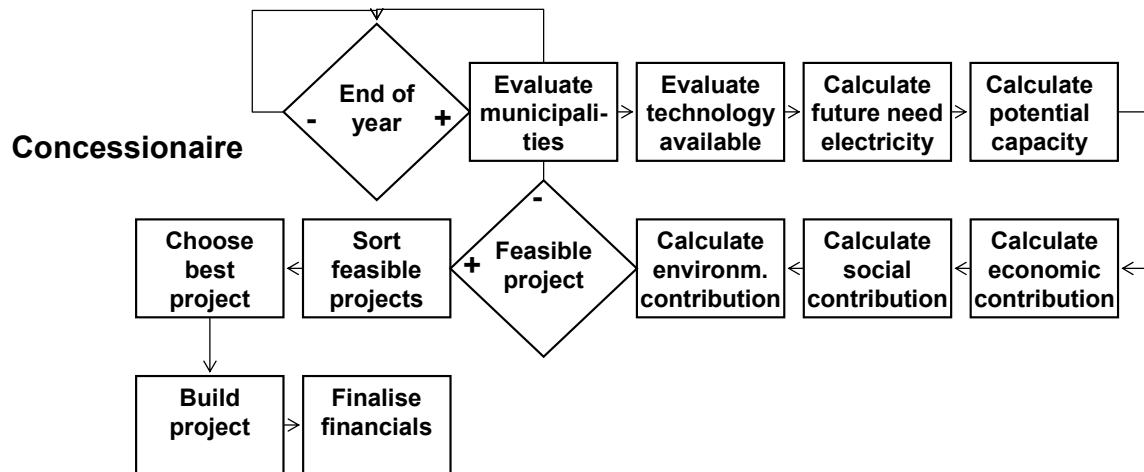


Figure 7- 4 Logic diagram for the concessionaires

The data that concessionaires use to determine the feasibility of their projects includes the characteristics of the different municipalities they cover (the number of households available, the size of the area, electrification ratio, household density, existence of grid lines (see appendix A1), associated costs with each project, potential revenues over the life time of the project and, if considered, the social and environmental consequences of their actions.

The fourth category of organisations is the local governments. Each government consists of three to seven municipalities and they receive a Municipal Infrastructure Grant (MIG) grant from the Department of Provincial and Local Governments (DPLG) to electrify these municipalities. The municipalities they govern are the same as those covered by the concessionaires, so their activities are interdependent. The location of local governments and municipalities they govern is illustrated in figure 7-5. There is no exact overlap between local governments and concessionaires, so some local governments have municipalities that are covered by different concessionaires⁴⁸. The options for electrification are: 1) extension of the current grid, 2) development of minigrids with the sugar mills as basis and 3) development of minigrids on the basis of fuel engines. The development of minigrids on the basis of sugar mills can only take place in those municipalities that have a sugar mill location. However, in comparison to the other two alternatives, it is an attractive option. It is through both the potential

⁴⁸ In 2005, the region of Umzinkulu was not part of Kwazulu Natal and governed by one of other districts in South Africa. However, in 2007 Umzinkulu became part of the province of Sisonke. Although not reflected in figure 7.4., these recent developments have been considered in this model.

production of biodiesel and the production of green electricity from sugar mills that activities of local governments and the bioenergy network are interconnected.



Figure 7- 5 Local government regions and municipalities in KwaZulu-Natal (Statistics SA 2005:3)

The logic diagram of local governments is presented in figure 7-6. Currently, there are a couple of ‘rules of thumb’ that local governments should follow to assess the feasibility of projects. For grid connections, the area should:

- contain bulk supply lines and have a density of 50 consumers/km²
- border bulk supply lines and have a density of 100 consumers/km²
- have connection costs lower than R6720 (C&V Consulting Engineers 2006:16).

For non-grid or mini-grid connections, Scottish Power used the following criteria:

- no grid electrification plans for at least 5 years
- density of 50 consumers/km²
- alignment of community expectation as well as potential institutional users (schools, clinics and others)
- isolated villages (Scottish Power 2003:7).

Finally, according to the department that provides electrification grants to local governments, they should base their priorities on those projects that have the lowest costs over the total life cycle of the project (installation costs, maintenance costs and costs of provision of electricity) (C&V Consulting Engineers 2006:8). These rules are reflected in the model. However, the use of different mental models will result in different interpretations of costs associated with each project and different interpretations about how to evaluate costs for each municipality. The different rules and their relation to the mental models are explained in more detail in section 7.2.2.

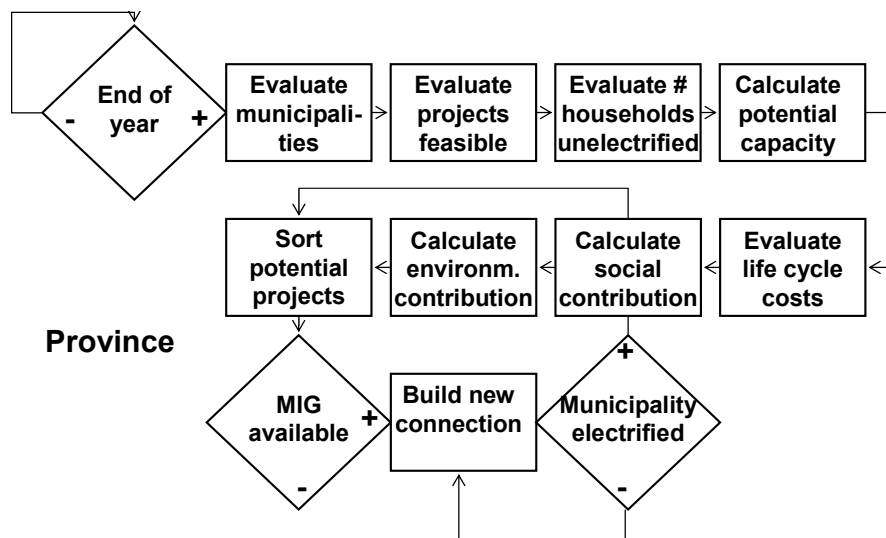
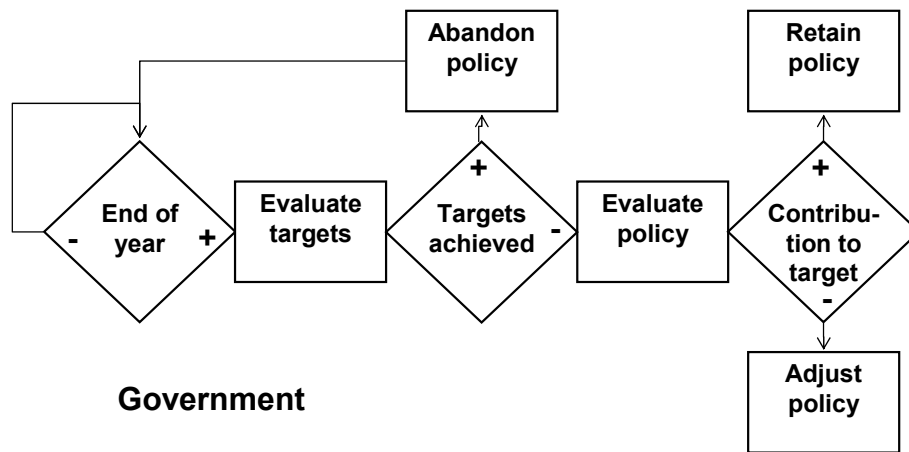


Figure 7- 6 Logic diagram for local governments

The final category of organisations in the model is the national government. Although the national government consists of a large number of different departments, each with

different interests in the evolution of the bioenergy network, their logic diagrams can be viewed as being the same in the first instance (see figure 7-7).



Government

Figure 7- 7 Logic diagram for government

In the model, the different departments in the government have the following strategic options:

1. Introduction of regulation.
2. Introduction of financial incentives.

In reality, they can also affect the model by providing information or advice to individual organisations or introducing voluntary schemes. Currently, there are a number of policy instruments in place that affect the evolution of the bioenergy network:

1. There is a national target of 10 TWh per annum of green electricity in 2013.
2. There is a national target of 3.5% biofuels of the total fuel consumption in 2013⁴⁹.
3. Petroleum diesel and petrol are taxed and there are tax exemptions for biodiesel and bioethanol production
4. Each local government receives a yearly MIG grant to electrify their municipalities.

The model considers both existing instruments in place as well as effects of new or adapted instruments on the evolution of the bioenergy network.

⁴⁹ In late 2007, this target has been revised downward from 3.5% to 2.5%.

7.2.2 Operationalisation of mental models

In chapter 5, specifically in section 5.4., it was argued that by systematically exploring how uncertainty is dealt with in mental models of organisations, it is possible to explore how organisational behaviour affects industrial network evolutions and the potential consequences of interventions to stimulate sustainable development. Two components of mental models were distinguished: 1) mental representations of the world and 2) cognitive structures that transform information into action, via the decision making process. Finally, it was argued that different ‘mental representations’ and different ‘cognitive processes’ can be distinguished on the basis of how they deal with the inherent uncertainty associated with strategic decision making.

This section illustrates how different sets of ‘mental representations’ and ‘cognitive processes’ can be used to explore different ‘mental models’ and how these ‘mental models’ can be operationalised into different scenarios. The different cognitive processes are based on the ‘strategic decision making’ model developed by Mintzberg, Raisinghani et al. (1976) and the different processes for mental representations are based on the analytical framework developed in chapter 2 (figure 2-2).

The scenarios are categorised according to the extent to which an organisation uses functional or implicit characteristics for mental representations⁵⁰ (F), individual biases (B) and social norms and values (S) in order to interpret their environment. Subsequently, organisations can use this information in different ways to inform their decision making process depending on their perception of uncertainty. These cognitive processes are categorised into three groups according to the extent to which an organisation perceives uncertainty and responds to it. This response is labelled in one of three ways as follows: rational (R), heuristics (H) and imitation (I). Figure 7-8 shows how a combination of different ‘mental representations’ and different ‘cognitive processes’ can be used to explore a whole range of different mental models and their consequences for the evolution of an industrial network.

⁵⁰ The categories and the associated labels are developed for notation convenience and do not reflect ‘absolute’ categories of different mental model representations or cognitive processes.

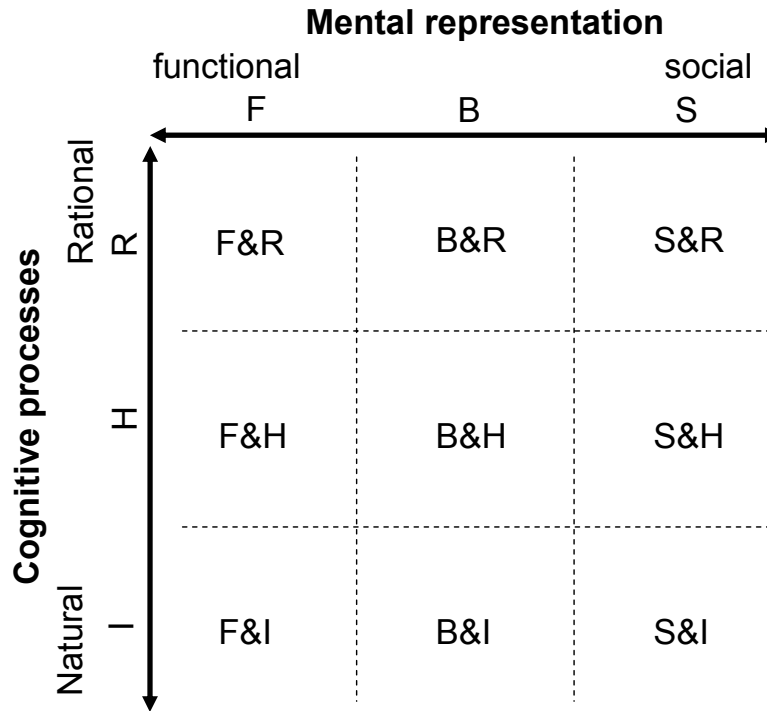


Figure 7- 8 Labelling the different mental models for scenario analysis

The fact that all organisations may use the same mental models does not mean, necessarily, that all organisations make the same decisions. Instead, a mental model only represents the causal relationships an organisation perceives, while the situation in which the mental model is used determines the variables and parameters that form the basis for the analysis. The sequential process of 1) interpreting the environment, and 2) making a decision, means that the perception of the environment and the cognitive process are interrelated with regard to the variables that are used to inform the decision process. However, the cognitive process of interpretation and decision making is independent of processes used to create the mental representation of the world that inform this cognitive process, even though the underlying system variables may be common to both. Figure 7-9 illustrates this distinction. This distinction is an important one, and needs to be recognised in the operationalisation of the scenarios.

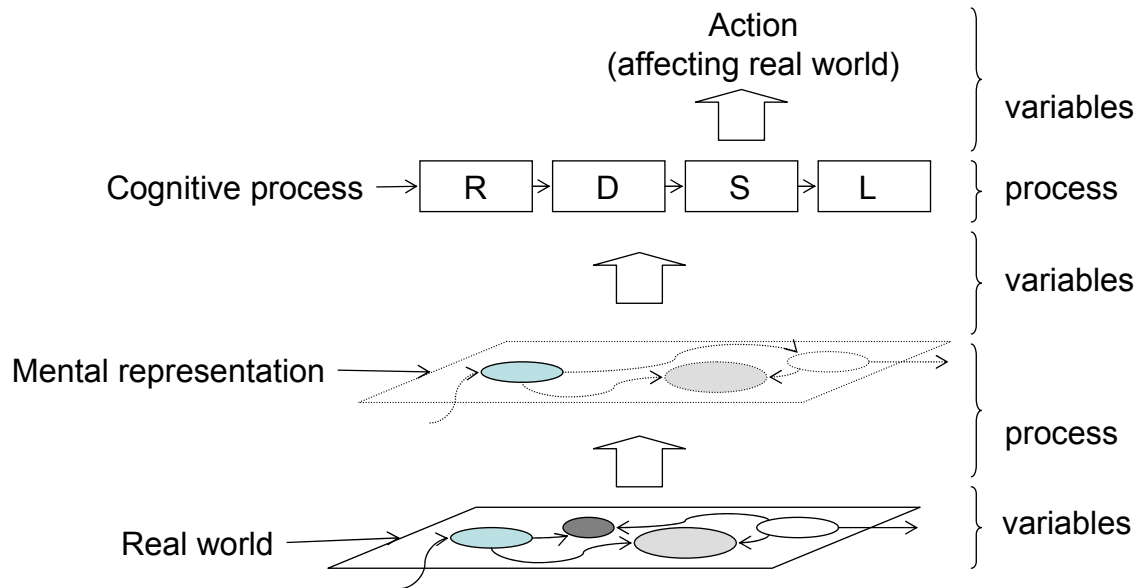


Figure 7- 9 Independency of mental model processes and interdependency of these processes through the variables

The next figure shows how this process of interdependent variables and independent processes is operationalised within the construction of the different scenarios.

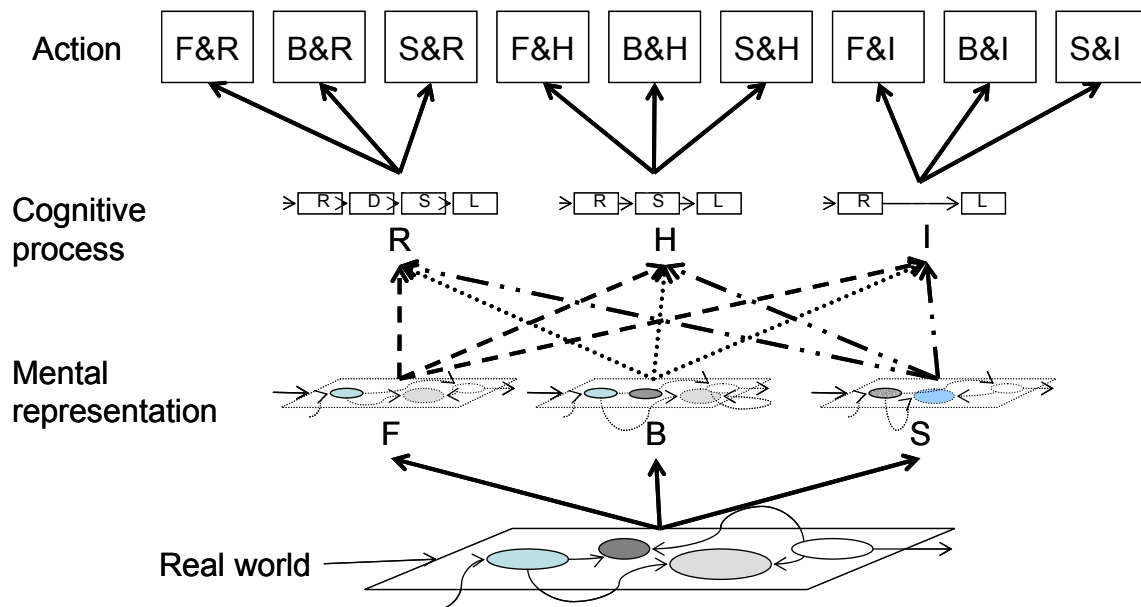
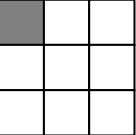
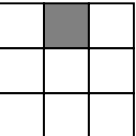
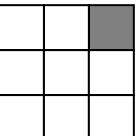


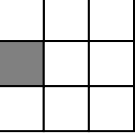
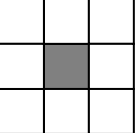
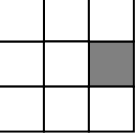
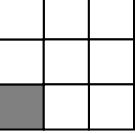
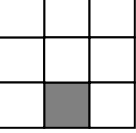
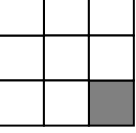
Figure 7- 10 Construction of the different scenarios on the basis of mental models, whereby each mental model is consists of a combination of a particular process reflecting a mental representation and a cognitive process

Figure 7-10 shows the nine different ‘mental models’ that are constructed, each forming the basis for one of the nine scenarios. The figure shows that different processes in the mental representations lead to different information being used in the cognitive processes. Subsequently, the use of different cognitive processes leads to different decision outcomes and therefore actions undertaken. This procedure for operationalising the mental models into scenarios explicitly recognises the inherent variety in complex systems. Although the scenarios are based on organisations applying the same mental models, the variety of behavioural actions of organisations is large. Each organisation has a different starting position, they are placed differently within the network, and their actions are affected by path dependence. This means that their ‘real world’ (see figure 7-10) is different at any point in time throughout the simulation. Furthermore, the interaction between organisations implies that the state of an organisation is constantly changing, fostering further variety between organisations within the network.

A brief description of the scenarios on the basis of different rules for mental representation and cognition is provided in table 7-1.

Table 7- 1 Description of the different scenarios for exploring evolutionary pathways in industrial networks

Mental models	Scenarios descriptions
<p>1 – F&R</p> 	<p>F: Organisations use functional characteristics to interpret their environment and select available alternatives.</p> <p>R: Organisations choose the alternative that maximises their individual utility.</p>
<p>2 –B&R</p> 	<p>B: Organisations use individual norms regarding the perceived uncertainty of options to interpret and constrain their alternatives.</p> <p>R: Organisations choose the alternative that maximises their individual utility.</p>
<p>3 – S&R</p> 	<p>S: Organisations use social norms and a perception of status to interpret and constrain the possible alternatives.</p> <p>R: Organisations choose the alternative that maximises their individual utility.</p>
<p>4 – F&H</p>	<p>F: Organisations use functional characteristics to interpret their environment and select available alternatives.</p>

	<p>H: Organisations calculate the payback time of each alternative and choose the alternative that satisfies the threshold.</p>
<p>5 – B&H</p> 	<p>B: Organisations use individual norms regarding the perceived uncertainty of options to interpret and constrain their alternatives.</p> <p>H: Organisations calculate an IRR for each alternative and choose the alternative that satisfies the individual norm⁵¹.</p>
<p>6 – S&H</p> 	<p>S: Organisations use social norms to inform heuristic threshold and a perception of status to interpret and constrain the possible alternatives.</p> <p>H: Organisations calculate an IRR for each alternative and choose the alternative that satisfies the individual norm.</p>
<p>7 – F&I</p> 	<p>F: Organisations use functional characteristics to interpret its environment and select available alternatives.</p> <p>I: Organisations imitate the behaviour of the organisation with the highest utility performance</p>
<p>8 – B&I</p> 	<p>B: Organisations use individual norms regarding the perceived uncertainty of options to interpret and constrain their alternatives.</p> <p>I: Organisations imitate the behaviour that is displayed most frequently within the network.</p>
<p>9 – S&I</p> 	<p>S: Organisations use social norms and a perception of status to interpret and constrain the possible alternatives.</p> <p>I: Organisations imitate the behaviour that of the organisation with the highest status in the network.</p>

7.2.3 Operationalisation in a bioenergy network

As discussed in chapter 6 and section 7.2.1, the bioenergy network consists of organisations that contribute to the industrial network evolution by making transformation-type and exchange-type decisions about resources. The transformation decisions involve the choice to adopt a particular technology, while exchange decisions involve choosing between different potential partners. This section will provide two

⁵¹ In comparison to scenario 4, the organisation uses an IRR threshold instead of a payback time threshold as an aspiration level. The reason for this is that in scenario 4 the organisation does not use the ‘perceived uncertainty’ in the decision making process and therefore applies a simple payback threshold. In scenario 5 & 6, the organisation uses the perceived uncertainty as a variable in the decision making process, which is reflected in the use of an IRR-threshold.

examples of how the different mental models forming the basis for the scenarios are operationalised into the organisational behaviour of organisations in the bioenergy network. These two span the whole range of different mental models explored. The full description of the operationalisation of all nine mental models can be found in appendix A3.

7.2.3.1 Operationalisation of scenario 1

Scenario 1 (F&R) is informed by a mental model in which organisations use functional characteristics to interpret their environment and subsequently choose those options that maximise their utility. The operationalisation of scenario 1 is provided in table 7-2

Table 7- 2 Operationalisation of scenario 1 (F&R)

F&R	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine costs and efficiencies of all options available	Evaluate utility of each technology and utility of non-action and choose option with maximum utility
<i>Exchange decision</i>	Contact all potential partners available	Evaluate price of each potential partner and choose the partners with the lowest prices

In other words, organisations determine how much money they would receive from placing the costs for the investment in a bank and they compare this to the returns from investing. They do not consider future uncertainties in terms of, eg variation in oil prices or electricity prices. In this mental model, the external world is perceived as static. In terms of partners, they base their decision only on price. For local governments, scenario 1 means that they prioritise projects on the basis of the connection costs per household and not on maintenance or life cycle costs.

7.2.3.2 Operationalisation of scenario 9

Scenario 9 (S&I) comprises a mental model, in which organisations use social norms and values to interpret their environment and subsequently imitate those organisations that have the highest status in the network. The operationalisation of scenario 9 is provided in table 7-3.

Table 7- 3 Operationalisation of scenario 9 (S&I)

S&I	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options socially accepted and evaluate their costs and efficiencies	Choose technology by imitating the organisation with the highest status in the network.
<i>Exchange decision</i>	Contact only potential partners with high status	Choose partners on the basis of highest status .

This scenario reflects a situation where organisations perceive the world as highly uncertain. Therefore, they use implicit social network characteristics to ‘make sense’ of their environments. From a cognitive perspective, they imitate each other rather than attempting to make individual decisions. This situation is reflected by the rules in table 7-3. Organisations only evaluate those technologies that are socially acceptable (in other words, they only consider technologies that are already demonstrated by other organisations in the network⁵²) and they only contact those organisations with a high status. In terms of cognitive processes, they imitate organisations with a high status rather than looking at the frequency of technologies adapted and they choose partners on the basis of their status instead of the received price.

7.3 Agent-based scenario analysis of the bioenergy network

This section presents and discusses the modelling results for the bioenergy case study. The results are discussed in three sections. The first section discusses the development of context scenarios and their implementation in a specific modelling platform AnyLogic™. The second section discusses the overall results of agent scenarios on the network evolution with an emphasis on the implications of these modelling results for the analysis and evaluation of bioenergy networks in particular and industrial networks in general. Section 7.4 discusses the use of modelling results to evaluate the contribution made to sustainable development by the network evolution

⁵² If no organisation has adopted any technology yet, they use their individual judgement about underlying risk propensity of technology options to determine their potential use.

7.3.1 Implementation of context scenarios

The nine scenarios described in the previous section form the basis for exploring potential industrial network evolutions. However, the context in which the model is developed is in itself a representation of the ‘mental model’ of the analyst. This ‘context scenario’ reflects the analyst’s world view on how the context in which the industrial network operates might change into the future. In traditional scenario analysis, one typically distinguishes between three such context scenarios. The first context scenario is a ‘business as usual’, whereby the analyst assumes that current trends in terms of market growth, external price effects (ie oil prices) or availability of resources can be extrapolated into the future. The second and the third context scenarios often represent either ‘pessimistic’ or ‘optimistic’ world views, whereby an analyst assumes that the external environment will either limit or promote the future the development of the industrial network. Each of these scenarios is described by specific values of key system parameters. The starting point for each of these three context scenario is similar, because it reflects the current situation in South Africa (which is fixed and known⁵³).

Table 7-4 represents the three different context scenarios that are developed for the case study of the bioenergy network. The figures in the ‘business as usual’ scenario are the current expectations for the growth rates of the external variables (see data in table 6.6. on basis of DME 2004; Statistics SA 2005; Coetzee 2006; Eskom 2007). The growth rates for the ‘positive’ and ‘negative’ scenarios are set within this thesis to represent different world views of an analyst.

Table 7- 4 Scenario analysis from the perspective of the analyst. Within each scenario, the potential industrial network evolutions can be explored by looking how different mental models affect the network evolution

	Growth electricity price	Growth demand electricity	Growth available bagasse	Growth oil price	Growth CO2 price	Growth population
Scenario A	10%	5%	5%	5%	15%	5%

⁵³ At least, the official figures are known. In South Africa, the total population and household density are estimations rather than actual measurements.

(positive)						
Scenario B (BAU)	3.14%	2.5%	2.5%	5%	10%	1.2%
Scenario C (negative)	-2%	0%	-2.5%	0%	0%	0%

The three scenarios explored in this thesis represent only a small set of a large number of different context scenarios that might be explored. The model is developed such that stakeholders interested in exploring different context scenarios than those presented in this thesis can interactively change the underlying assumptions of the context scenarios. Figure 7-11 shows the interactive display that allows different stakeholder to set different initial conditions and context scenarios. This is a valuable educational tool for stakeholder engagement. The model can, in real time, be run for any numerical value of the parameter space, simply by sliding the cursor to any point in the range considered for each parameter. This allows the analyst to adapt the analysis to accommodate his/her individual world views.

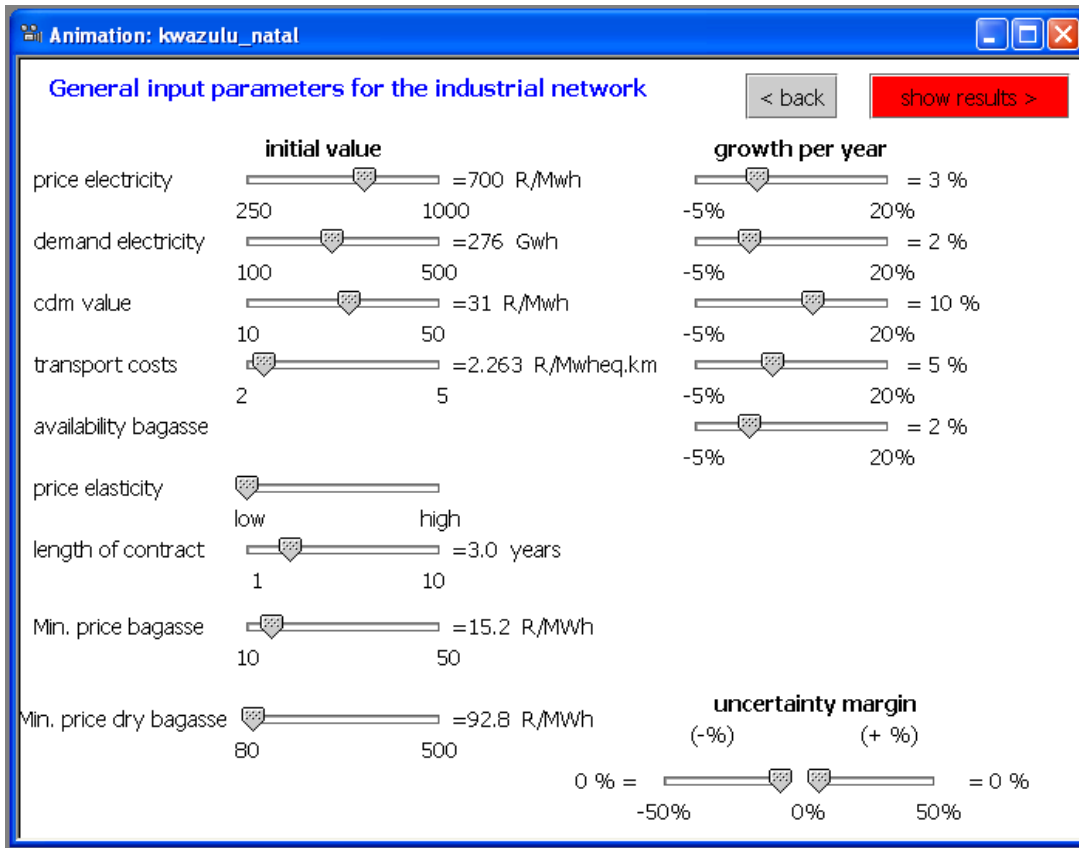


Figure 7- 11 Snapshot of interactive display for demonstration projects with decision makers

Furthermore, the model provides a visualisation of the network evolution at runtime (see figure 7-12). The visualisation shows the position of the sugar mills (red stars) and whether they have invested in a pelletising capacity (the yellow bar). The height of the yellow bar reflects pelletising capacity installed. The red circles represent either combustion or gasification technologies installed by sugar mills. The size of the circle reflects the capacity, while the letters 'G' and 'C' indicate the sugar mill's choice for either gasification or combustion. The green circle represents the coal-fired power station of ESKOM and any investments in cofiring. Purple, orange and brown circles represent respectively bioethanol, biodiesel or biogel producers entering the network. The position of the circle indicates their location within the region. The lines represent the contracts for either wet or dry bagasse between sugar mills and independent producers, whereby the width of the line indicates the volume of bagasse exchanged. Finally, the visualisation shows the number of grid connections, minigrid connections on the basis of fuel engines, connections via sugar mills and the number of solar systems

installed in the network at that particular time. Figure 7-12 provides a 'snapshot' of the visualisation, while figure 7-13 shows how an analyst can follow the network evolution of the bioenergy network under a particular scenario.

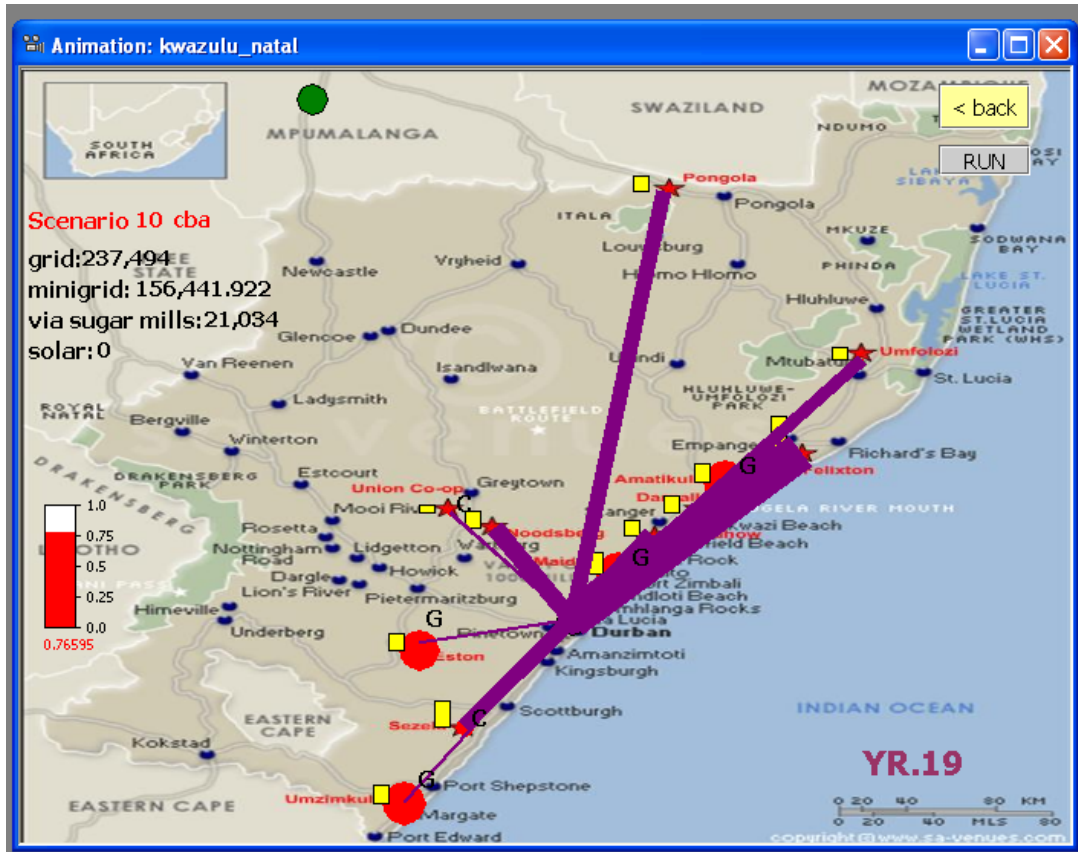


Figure 7- 12 Visualisation of the evolution of the bioenergy network

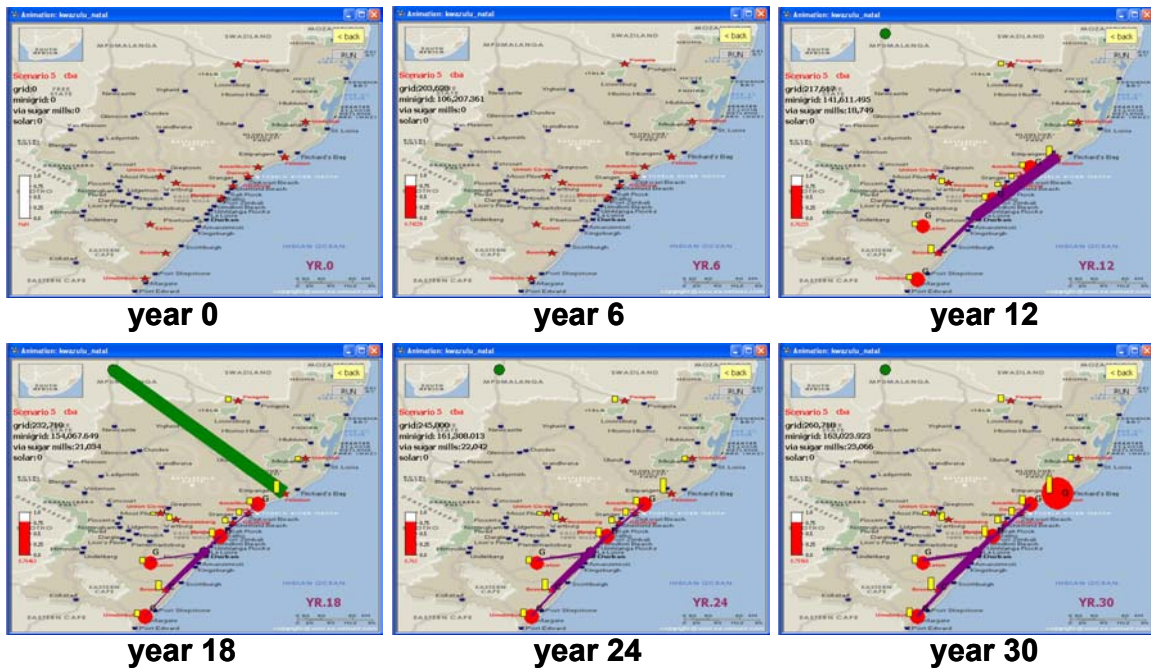


Figure 7- 13 Dynamic visualisation of the bioenergy network over a period of 30 years

7.3.2 Results of agent scenarios

This section shows the modelling results for the nine agent scenarios within the 'business as usual' context. Modelling results are obtained on the basis of four system characteristics identified as the main contributions to sustainable development:

- 1) the total electricity and/or energy produced by each organisation in the network and associated economic value of the network,
- 2) the total CO2 profile for the network,
- 3) the electrification rate for individual municipalities, and
- 4) the choice of technologies employed for electrification.

However, these "system" outputs are not the only results that can be obtained from interpretation of the agent-based models. Throughout the analysis, each decision is recorded, and the logic behind each decision can be compared to the logic of the initial assumptions that form the basis of the scenario. This is a form of model validation. Furthermore, the development and structural evolution of each bioenergy network is visualised dynamically within the actual geographical dimensions of KwaZulu-Natal (as displayed in figure 7-13).

The full set of modelling results can be found in appendix A4. This section will discuss selected results which show how organisational behaviour in industrial networks give rise to complexities commonly associated with the development of new networks:

1. The role of resource scarcity in network evolutions.
2. Path dependencies associated with infrastructure development.
3. Co-evolution and lock-in situations of innovations.
4. Inertia and the role of learning in industrial network evolutions.

7.3.2.1 Interpretation of modelling results

The modelling results displayed in this section are on the basis of the ‘business-as-usual’ context scenario. The modelling results show how, given the conditions set in table 7-4, the nine different agent scenarios (each representing a different ‘mental model’) result in different network evolutions. Modelling results show the energy produced by organisations in the network (figure 7-14), the total number of household connections in each of the local government regions (figure 7-15) or specific comparisons of network features (ie prices, configuration etc.) between different agent scenarios. Furthermore, the modelling results either show how network characteristics change over 30 years (eg figure 7-14 and 7-15) or provide snapshots of the network at a

particular point in time (figure 7-17 and 7-22). Since some figures present a large quantity of modelling results, their legends are placed on the page before or after the figure. The position of the legends is indicated in the caption of the figures. The colours used to represent either individual organisations and/or local governments are consistent throughout this thesis.

The emphasis in this section will be on the implications of using agent-based scenario analysis and insights and understanding that can be obtained from this methodology. Furthermore, this section will highlight the significance of these modelling results for the development of interventions and associated challenges in interpreting the variety of information that this methodology provides. Although the results are specific to the case study of the bioenergy network in regional South Africa, the lessons learned from these explorations can be transposed to other complex adaptive systems.

■	SM12
■	SM11
■	SM10
■	SM9
■	SM8
■	SM7
■	SM6
■	SM5
■	SM4
■	SM3
■	SM2
■	SM1
■	GEL
■	IFP
■	IEP
■	IPP
■	Generator

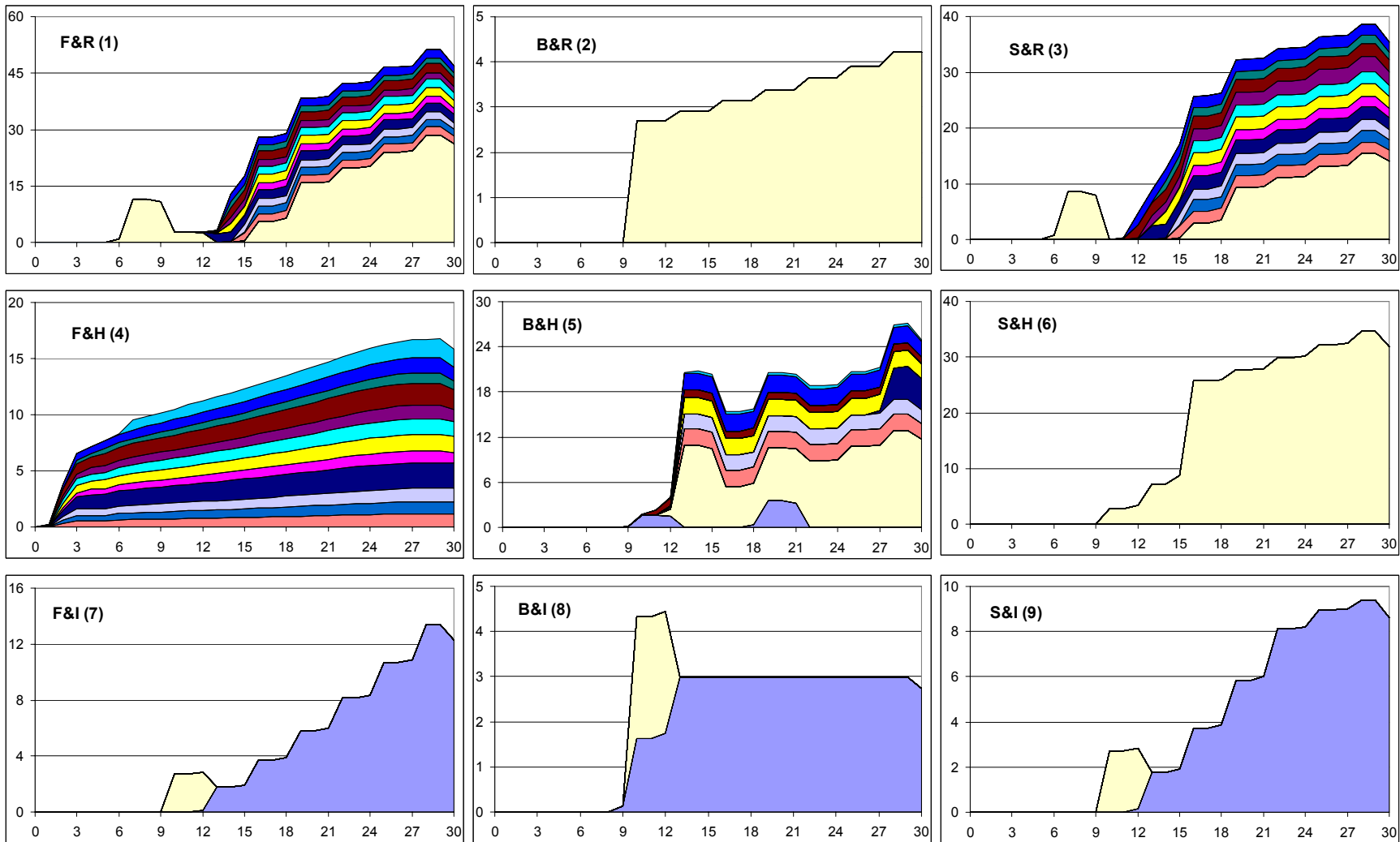


Figure 7- 14 Energy production in PJ by the different organisations in the bioenergy network over a 30 years (legend previous page)

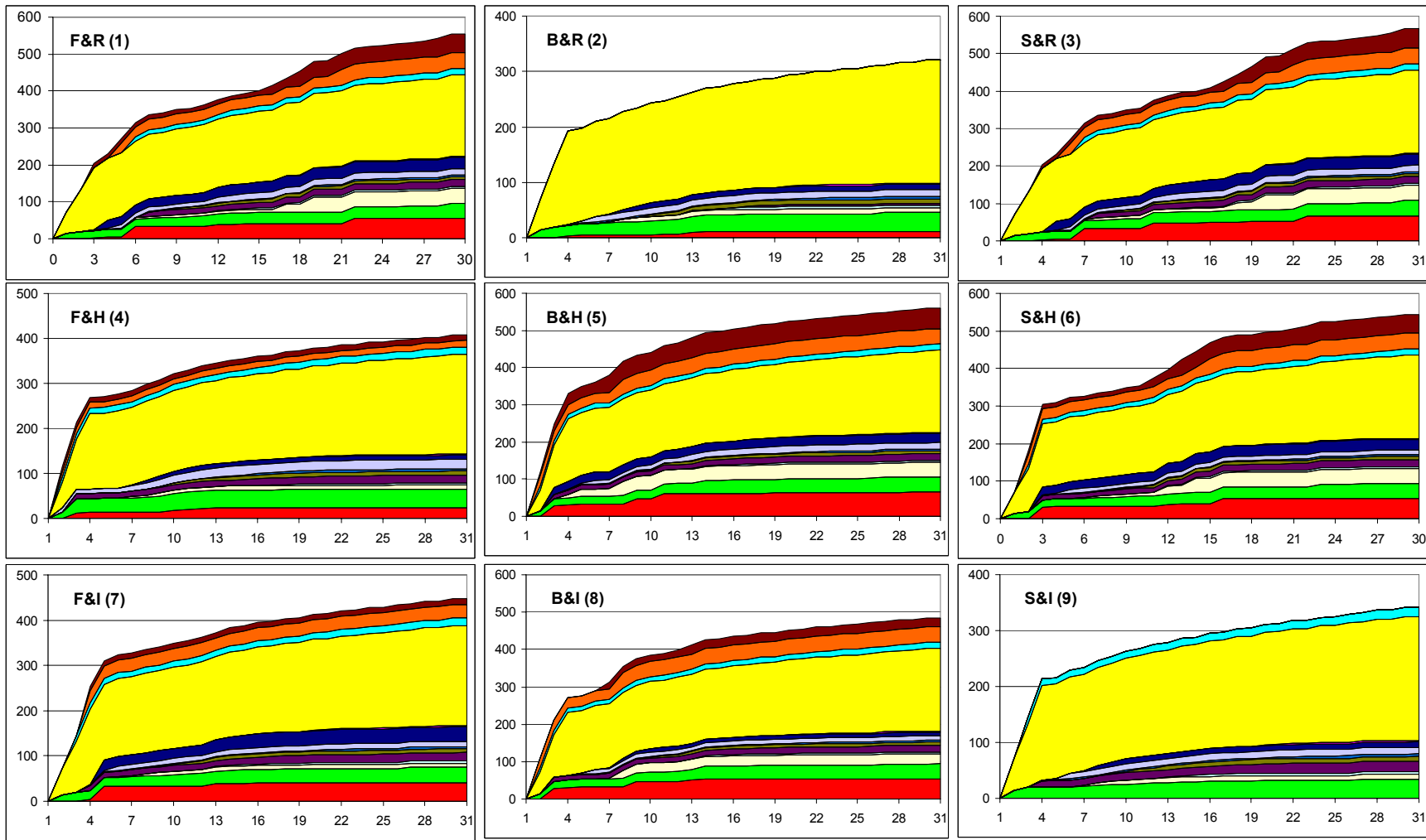


Figure 7- 15 Total household connections (x 1000) by local government and concessionaires in the bioenergy network over a 30 years (legend next page)



Figure 7-14 illustrates the different potential bioenergy network evolutions associated with different agent scenarios within the context of a ‘business as usual’. The results show a high diversity in the different evolutionary pathways. The only commonality is that most scenarios, over the 30 year time frame, produce increasingly more energy, which is associated with the increased availability of bagasse and the increased oil and electricity prices associated with the ‘business as usual’ scenario.

Figure 7-15 shows the results of infrastructure development in each of the nine scenarios. The results show less diversity in the behaviour of local governments and concessionaires than the organisations associated with the energy production. The reason

for this is that actions of local governments dominate the infrastructure development. Their actions are mostly based on the amount of annual MIG allocation they receive, and their evolution is therefore less dependent on the evolution of the other system structures. However, despite the importance of the MIG allocation for the different network evolutions, there are clear differences in the evolutionary pathways for infrastructure development on the different scenarios.

More results on energy production, technology uptake and diffusion, CO₂ profiles and individual electrification rates for each of the 50 municipalities in each scenario can be found in appendix A4. The remainder of this section will focus more specifically on the insights that can be gained from this analysis about the complexities in industrial network evolutions.

7.3.2.2 Resource scarcity

The role of resources and resource scarcity is a highly debated subject in the evolution of industrial networks. Especially in the early 1970s, fuelled by the Limits to Growth model, the so called ‘neo-Malthusians’ viewed that economic growth inherently results in environmental pollution and a destruction of all natural resources, while others argued that the market economy would respond to scarcity in resources with technological ‘fixes’ and price responses (Ayres 1993:191).

In the bioenergy case study, resource scarcity is represented by the amount of bagasse (either dry or wet) available within the network. Figure 7-16 shows the price for both dry and wet bagasse for scenario 5 and 8.

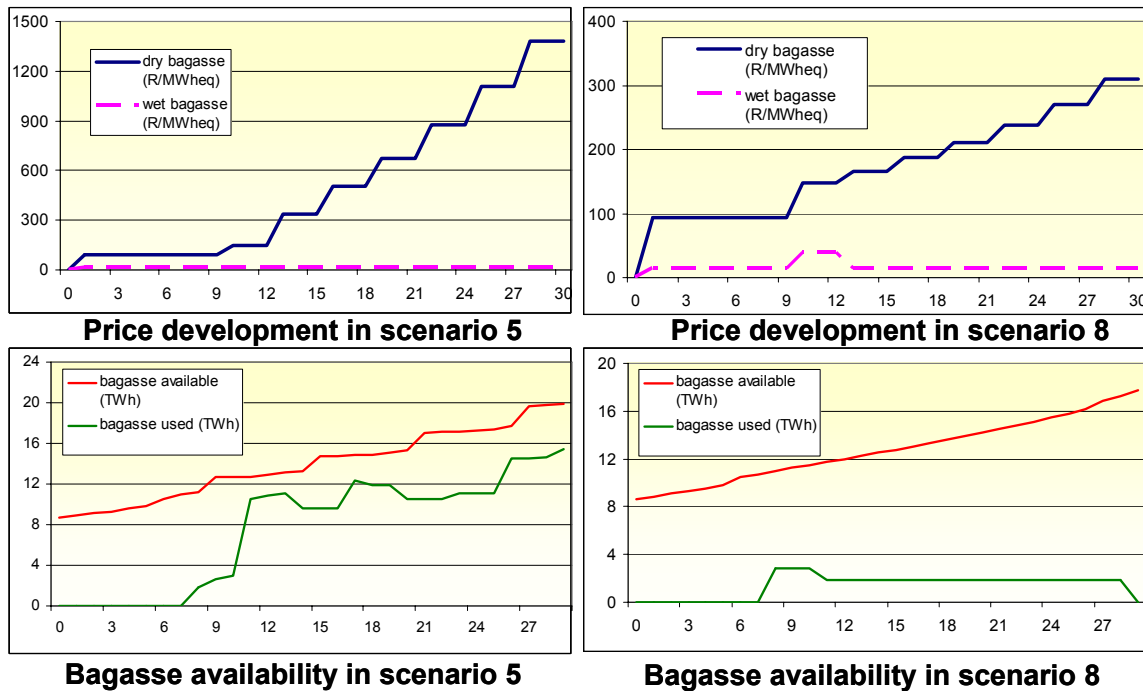


Figure 7- 16 Comparison of price development for both dry and wet bagasse and the associated availability of bagasse in the network over 30 years between scenario 5 and 8

Figure 7-16 shows bagasse availability and associated price developments within two networks. The results show that there is not a simple relationship between the availability of bagasse and the price of bagasse. Scenario 5 shows that the price trend is independent from bagasse availability in the network. Between years 12 and 30 the price of bagasse is increasing, while bagasse scarcity fluctuates over the same time period. This shows that it is not only resource scarcity that is reflected in a price, but that price developments depends on internal constraints and external market drivers. This also means that resource scarcity does not necessarily provide organisations with a clear signal to innovate through investment decisions or new partnerships.

These findings also have important implications from an analytical perspective. They show that markets can not be seen as independent entities, which efficiently and effectively allocate resources between buyers and suppliers. Instead, the market should be viewed and analysed as an integral part of a larger system, which affects and is affected by developments within the market itself; and wherein external drivers can impact on what organisations are willing to spend. In scenario 8, the price for dry bagasse is considerably lower than in scenario 5, supposedly reflecting lower resource scarcity. However, that is not the only reason. If one compares the number of organisations within the network (see figure 7-14 in section 7.3.2), and the availability of both dry and wet bagasse (see figure 7-16), one can see large differences in the structure of the network. There is only supplier of dry bagasse in scenario 8, while in scenario 5 all sugar mills can supply dry bagasse. Still, the price of dry bagasse is lower in scenario 8 than in scenario 5. The main reason for this is that in scenario 5 bagasse is used for the production of biofuels (although there is local electricity production), while in scenario 8 bagasse is transported for electricity use (see figure 7-17). The lower prices for electricity, together with the substantial transport costs, ensure that ESKOM (represented as PS in figure 7-17) bids at a lower price for the resource. Furthermore, there is no localised production of electricity in scenario 8, because sugar mills base their investment decision on what the majority has adopted. In this case, this means that there are no investments taking place by sugar mills (see figure 7-14).

The main conclusion from this section is that the use of equilibrium models for representing markets is an oversimplification of reality, especially if there is only a limited number of organisations operating within a particular network. The methodology developed in this thesis allows for explicit consideration of the complex processes that drive organisational decision making, and their impacts on emergent markets and associated prices.

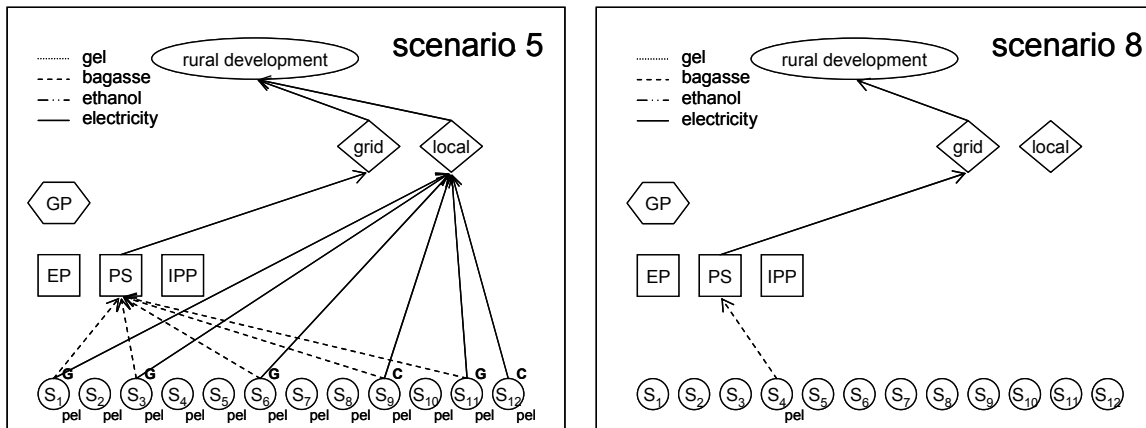


Figure 7- 17 Comparison of network configurations for scenario 5 and 8 in year 24⁵⁴

7.3.2.3 Lock-in of technologies

The role of “lock-in” of technologies is an important topic in literature on sustainable development. Here, one is concerned with early investments which might subsequently hinder or block other investments which could lead to more sustainable outcomes overall. Early lock-in into inferior technologies and/or infrastructure with limited contributions to sustainable development diminishes the possibility for more radical technologies to enter the network, even when they are superior in terms of their performance (Carrillo-Hermosilla 2006; Sartorius 2006). Lock-in has been observed in several historical case studies (David 1985) and has been the subject of several important conceptual contributions about the impact of randomness on the potential outcomes of competing technologies (Arthur 1989; Witt 1997).

In the bioenergy case study, lock-in is an important phenomenon with substantial impacts on the overall network evolution. This is demonstrated on the basis of a comparison between the evolutionary pathways of scenario 3 and 6.

⁵⁴ EP = Ethanol Producer, PS = is current Power Station located in Majuba, IPP = Independent Power Producer and GP = Gel Producer. In terms of technologies, C = Combustion, G = gasification and Pel. = pelletising technologies.

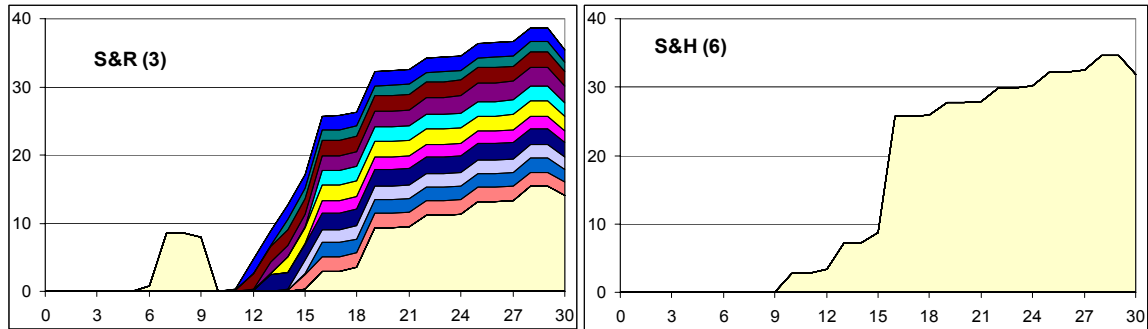


Figure 7- 18 Comparison of the total energy production (in PJ) of scenario 3 and 6 over 30 years (see legend next page)

Scenario 3 is comparable to scenario 6 in terms of the decision rules employed. In both scenarios, social embeddedness plays an important role, which means that the potential set of decision options explored depends on the actions of other organisations in the network. As long as no single organisation has invested, each agent in the simulation will evaluate all possible alternatives. The only difference between scenario 3 and 6 is that the eventual decision in scenario 3 is based on rational behaviour, while in scenario 6 aspiration levels are used to determine the value of an investment.

As can be seen in figure 7-18 differences between scenario 3 and 6 in year 11 consist of some localised electricity production. In both scenarios all sugar mills have invested in pelletisers and in both scenarios an ethanol producer is active on the market. The only difference is that in scenario 3 two sugar mills have just invested in gasification technologies. This small difference in the system state has eventually an important impact on the network evolution. In scenario 3, all sugar mills have invested in gasification technology in year 15 (see figure 7-18), while in scenario 6 no local production of electricity takes place. Figure 7-19 shows the total installed capacity (in MW) of sugar mills.

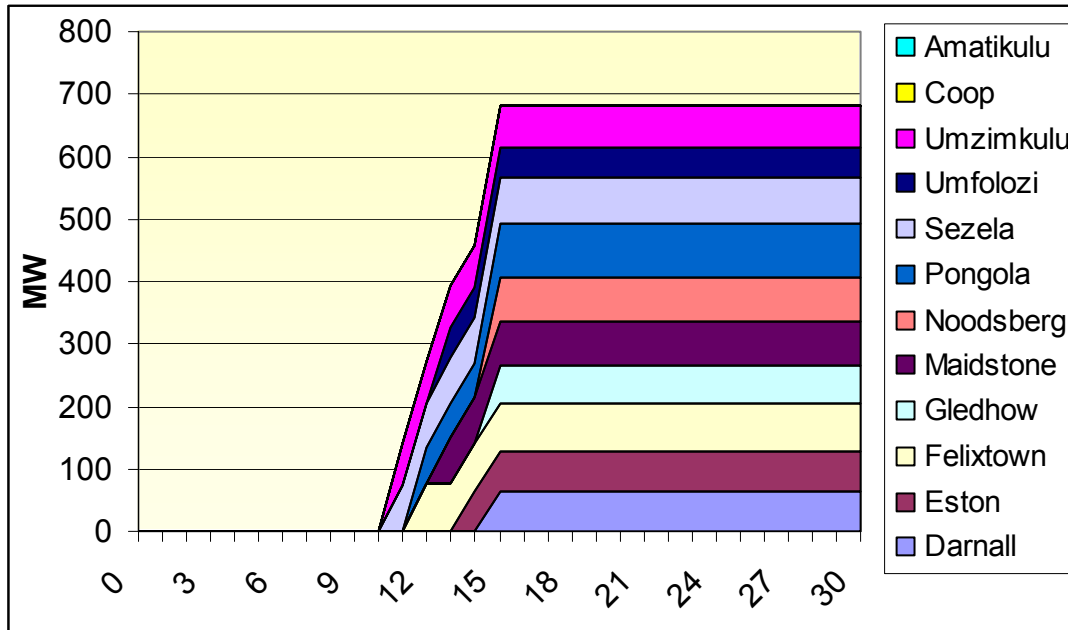


Figure 7- 19 Total installed capacity of sugar mills (in MW) in scenario 3 over 30 years

The process of lock-in and its implications for the bioenergy network are similar to the results of conceptual simulation models, as developed by Arthur (1989) and Abrahamson and Rosenkopf (1997). In other words, the model results confirm that small social differences can have important impacts on the evolution of technologies. However, instead of exploring lock-in situation on the basis of random numbers, the bioenergy case study demonstrates that regardless of any randomness or uncertainty in either data or processes small differences in the actual location and size of organisations can have an important impact on the network evolution as a whole.

7.3.2.4 Path dependency

Path dependency, like lock-in phenomena, focuses on how contingent, non-reversible decisions can affect the evolution of systems. However, the focus of path dependency is merely on the co-evolution between individual decisions and the system evolution in general rather than between two competing technologies (Sterman and Wittenberg 1999; Harding 2002). In the context of industrial networks, path dependency is related to the innovative and adaptive capacity of industrial networks and therefore an important feature for sustainable development (Vega-Redondo 1996; Könnölä 2006; Sartorius 2006).

Path dependency is especially relevant for energy systems, where the life time of investment decisions is often more than 20 years. In other words, a strategic investment decision today affects the network evolution for the next 20 to 25 years. Figure 7-20 shows the importance of path dependency in the bioenergy network by comparing scenario 1 with scenario 4. Both scenarios are based on a rational view of the world (ie use of functional characteristics only). However, in scenario 4 organisations base their decisions on an aspiration level whereas in chapter 1 they make their decisions on a rational choice to maximise utility.

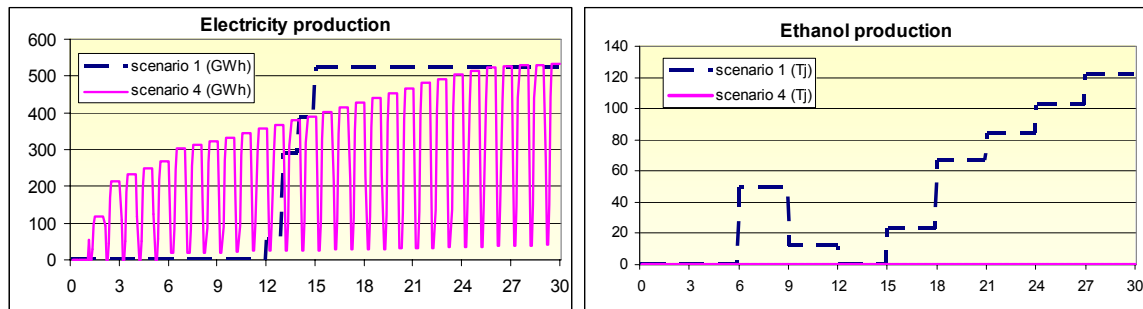


Figure 7- 20 An illustration of the importance of path dependency on the bioenergy network evolution by comparing scenario 1 and 4

In scenario 4, organisations have access to and use the same information as in scenario 1. However, they use a different cognitive rule to decide whether a technology should be implemented or not. In scenario 1, this means that the sugar mills only invest in generation capacity in year 12, while in scenario 4 sugar mills decide to invest in generation technology immediately. The difference in decision rules has important implications for the network evolution. In scenario 4 sugar mills opt for combustion technology and do not invest in pelletising. This has two consequences. Firstly, it limits the possibility for an ethanol producer to enter the market. Secondly, this means that they can only produce electricity for those months that bagasse is available (see the 'saw tooth'-shape production pattern for electricity in figure 7-20). There is only one organisation that makes a decision at a later point throughout the network evolution (the smallest sugar mill in the region), which subsequently installs both pelletising capacity and gasification. In scenario 1, on other hand, sugar mills only decide to invest in generation capacity in year 12. It allows the entrance of an ethanol producer, which stimulates the development of pelletisiers. Furthermore, the difference in the external

environment in which the sugar mills operate makes them opt for gasification rather than combustion.

Similar path dependencies can be observed in scenario 5. Figure 7-21 and 7-22 shows the different infrastructural shifts in the network and the associated consequences for the further development of the network.

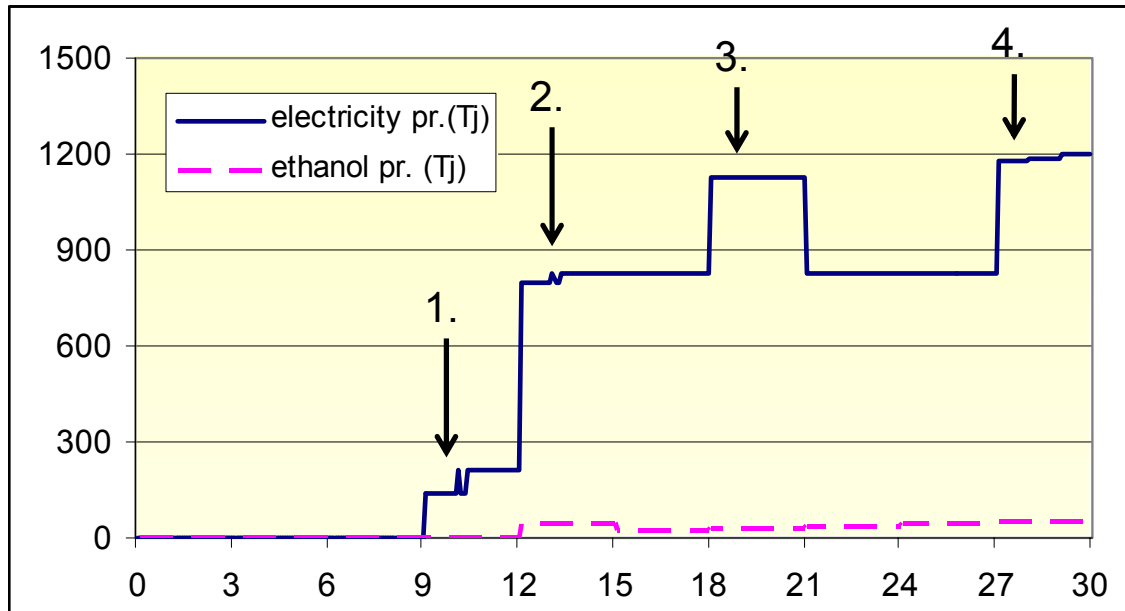


Figure 7- 21 The production of electricity and ethanol in scenario 5 over 30 years

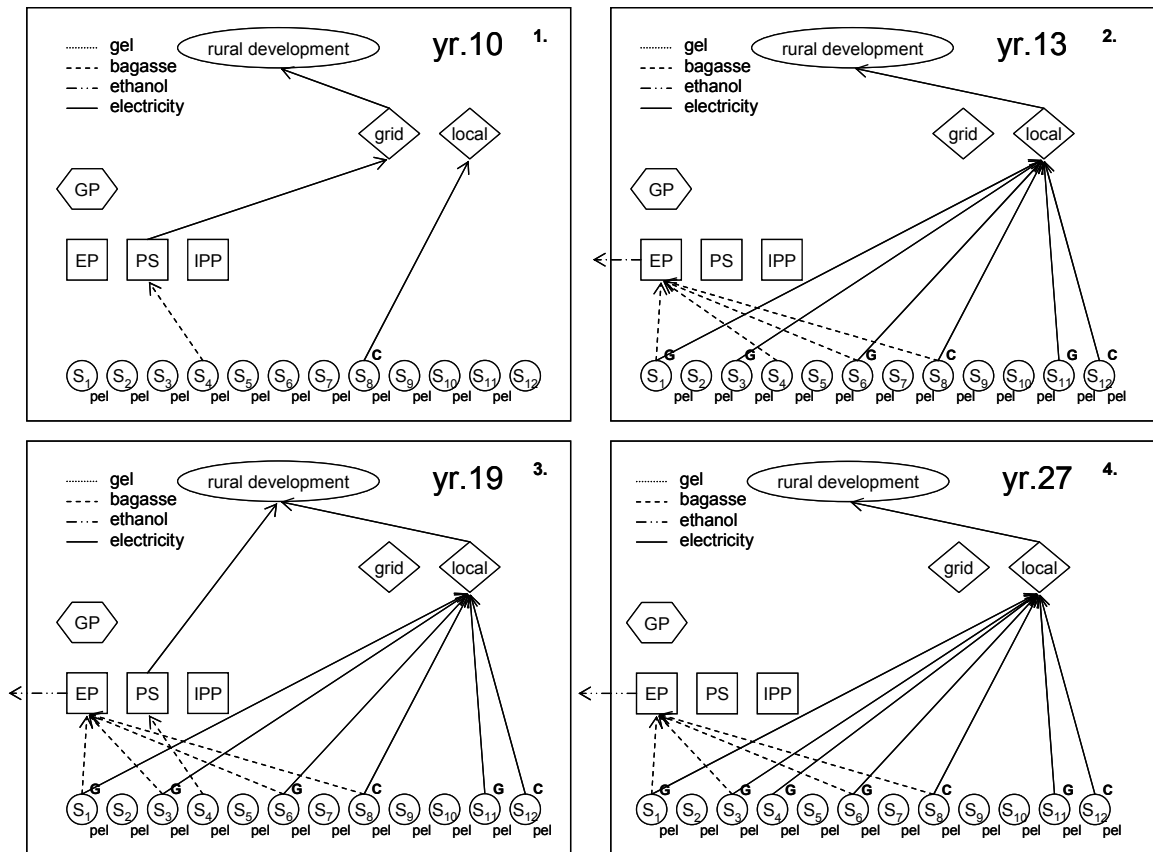


Figure 7- 22 Network configurations associated with the different production patterns of electricity and ethanol in scenario 5

Those sugar mills that invest early are locked into combustion technologies (S₈ and S₁₂), while others at a later stage in the network (with only 3 years in between the decisions) opt for gasification (S₁, S₃, S₆ and S₁₁). Others that do not invest in gasification technologies become locked into a situation where the opportunity costs of using bagasse for localised electricity production outweigh the economic benefits of producing locally. Furthermore, figure 22 shows how relational implicit characteristics impact on the relationships between organisations, whereby initial choices for suppliers create dominant network configurations. Sugar mill 1, 6 and 8 establish at an early stage contracts with the independent ethanol producer and retain their contracts throughout the simulation time span. Finally, it shows how independent producers are vulnerable to strategic behaviour of sugar mills. The electricity generator (PS) produces electricity initially on the basis of a single contract, but competition from both localised production within the sugar mills as well as from the ethanol producer drive the power station out of the network.

The results in this section demonstrate two advantages of the agent-based scenario analysis. Firstly, they reflect simulation models that engage with the non-linearities of complex systems. This is an advantage over other modelling approaches, most notably system dynamics, in that it shows how small deviations in the initial conditions of firms can have important consequences for their behaviour and position within the network evolution. Furthermore, the agent-based scenario analysis provides insights in the important implications of different decision rules on the network evolution. It shows that if one starts considering behaviour that deviates from the traditional assumption of rationality, many more evolutionary pathways are possible and understandable than traditionally envisioned.

7.3.2.5 Inertia and learning

Learning is seen as the true art of strategic decision making (Geus 1999) and is argued to be the most important process in creating a more desired future (Senge 2003). However, it is also argued that organisations have little and confusing evidence to learn from (March, Sproull et al. 1991; Levinthal and March 1993), which means that there is often organisational inertia to change within organisations (Hannan and Freeman 1984) or between organisations (Kim, Oh et al. 2006). In these circumstances of high uncertainty, it is argued that institutional processes of interorganisational imitation play an important role in when and why organisations change their behaviour (Haunschild and Miner 1997). ‘Learning through institutional processes’ resembles so-called “first-order” learning, whereby an organisation retains the same decision processes but adjusts its norms and values impacting on the decision. ‘Learning through imitation’ resembles “second-order” learning, whereby an organisation changes its decision process rather its norms and values (Argyris and Schon 1978)⁵⁵. Again, the question is how each of the processes affects industrial network evolution and whether it is possible to depict processes that are more or less important for sustainable development.

The impacts of inertia and learning are explored by integrating different learning processes in the mental models of organisations. Scenario 1 represents a system in which organisations neither learn from, nor have any inertia towards organisational or structural change within the network. Scenario 2, 5 and 8 represent scenarios where

⁵⁵ More details on the role of learning in strategic decision making has been provided in section 3.6.1. of chapter 3.

organisations have individual norms representing risk aversiveness, which subsequently impacts on their investment decisions, as well as decisions on exchange relationships. In these three scenarios, agents use individual norms representing risk aversiveness and they base their decisions to interact with others on consideration of trust and loyalty perspectives. In short, this means that they prefer to deal with those organisations they already know. Scenarios 7, 8 and 9 explore how learning through organisational imitation affects the network evolution, while scenarios 3, 6 and 9 explores how social embeddedness provides a form of learning.

The impact of inertia and learning on the industrial network evolution are represented in figures 7-14 and 7-15 in section 7.3.2, which show the number of household connections and the total energy production for any of the scenarios. Without a full appreciation of the performance of any of these scenarios in terms of sustainable development, it is not possible to depict a clear relationship between the impacts of inertia and learning on sustainable development (the evaluation of sustainable development will be discussed in section 7.4). Furthermore, such analysis requires a larger set of context scenarios, whereby the impact of inertia and learning are evaluated under a larger range of context scenarios. A full analysis of the relationship between these two processes and sustainable development is outside the scope of this thesis. However the methodology developed in this thesis allows for the exploration of such relationships.

Still, some preliminary conclusions can be drawn between the relationship of inertia and learning in the context of industrial networks. Firstly, the results show that inertia within an environment that causes agents to make rational decisions or which base their decision on a majority, limits the evolution of a bioenergy network. This is clearly demonstrated in scenarios 2 and 7. However, inertia in combination with aspiration levels does allow a bioenergy network to evolve (scenario 5).

The question remains whether these relationships also hold for other industrial networks. Furthermore, the results show that learning through imitation and learning through social embeddedness have different impacts on the network evolution. Learning through imitation results in industrial network evolutions that have similar features. In other words, network evolutions in which learning through imitation takes place show less diverse outcomes irrespective of the individual perceptions that organisations have

about their environment. On the other hand, learning through social embeddedness provides an array of different network evolution depending on the exact rules of that organisations use for their decision making. From a perspective of stimulating sustainable development, learning through imitation might be preferred in those context situations of high risk where developments can potentially have negative effects on the environment. On the other hand, learning through social embeddedness is preferred in those situations where there are more opportunities for different forms of sustainable development. Again, these preliminary conclusions have to be confirmed with more rigorous analysis of different context scenarios and a larger range of industrial network applications.

7.4 Functional and Structural System Evolutions

The previous section has showed how the complex processes that characterise industrial network evolutions can be analysed and explored using agent-based scenario analysis developed in this thesis. However, these observations have been made on a generic level looking at the different decisions, technology uses and system outputs that can be observed. This section will focus more specifically on determining the extent to which these evolutions / pathways are consistent with sustainable development, using the framework and functional and structural indicators developed in chapter 4.

Chapter 4 suggested four structural indicators to evaluate sustainable development of industrial networks: 1) efficiency, 2) efficiency 3) resilience and 4) adaptiveness.

The indicators used to measure efficiency and effectiveness are provided in table 6.10 and 6.11 in chapter 6, and repeated below.

Table 6-11 Measuring the efficiency of a bioenergy network.

	Contribution	Resource Input
Efficiency (economic)	Value of total energy produced (electricity * price electricity + bioethanol * price bioethanol + bioliquid * price bioliquid + biogel * price biogel)	Value of bagasse used in the bioenergy network (value dried bagasse * volume dried bagasse + value wet bagasse * volume wet bagasse)
Efficiency (environmental)	Total CO ₂ emissions averted	Total CO ₂ content bagasse entering bioenergy network
Efficiency (social)	Total GJ of green energy (electricity + gel) provided to rural households	Total GJ of bagasse entering the bioenergy network

Table 6-12 Measuring the efficiency of a bioenergy network.

	Economic value contribution	Total value of the system
Effectiveness (economic)	Total profits made by all organisations including tax benefits from government.	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.
Efficectiveness (environmental)	Total value of CO ₂ emissions averted (tonnes of CO ₂ averted * value of CO ₂ under CDM)	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.
Effectiveness (social)	Total value of green energy provision calculated by multiplying the quantity of electricity + gel provided to rural households multiplied by price of electricity and gel to households.	Total capital costs (including governmental subsidies) used to develop the system + the value of bagasse inputs.

We recall that contributions to sustainable development require consideration of the structural features of industry networks, in addition to the functional characteristics mentioned above. The concepts of resilience and adaptiveness are also discussed in chapter 6. In summary, resilience is determined by the excess capacity the bioenergy network has to provide a particular contribution, and the number of organisations that are able to provide that contribution. Diversity is determined by the mix of different resource inputs, technologies and resource outputs associated with organisations that provide a particular contribution.

The sustainable development of the system is reflected in three indicators: 1) cumulative profit of the organisations within the network (including the government, where subsidies are treated as expenditures and taxes as revenues), 2) total CO₂ emissions averted and 3) number of households that are connected to electricity (or are provided with biogel) in those municipalities with the lowest electrification rate.

The results are discussed in three sections. Firstly, the analysis of structural features is discussed. Secondly, the analysis of functional features is discussed and finally an overall evaluation of the sustainable performance of different evolutionary pathways is offered. The results will be discussed on the basis of specific examples. Full results are provided in appendix A4.

7.4.1 Interpretation of modelling results

The modelling results in this section show the overall system performance of any of the different agent scenarios. The first section shows the functional performance criteria (their economic, environmental and social contributions as defined in chapter 6), while the second section shows the structural performance criteria for each of the three functional contributions. The presentation of both sets of modelling results can be interpreted in the same way. In the figures, the x-axis represents the 30 years over which the different evolutionary pathways are analysed. The y-axis represents the relative performance of the nine different evolutionary pathways in terms of their functional or structural performance for the three different contributions to sustainable development. In each graph, the performance of a scenario in a particular year is compared to the performance of other agent scenarios in that year using a linear value function. This means that a network that provides twice as much economic contribution is valued twice as high. This results in an overall score for each performance criteria for each year for each scenario ranging from 0 for the lowest performance to 1 for the highest performance. This exercise is repeated for any given year and for the three different contributions towards sustainable development. Since some figures show system performances for all of the agent scenarios (to allow for comparison), the legends are sometimes placed at the page before or after the figure. This is indicated in the caption of the figure. Furthermore, the colours used to indicate different agent scenarios are consistent throughout this section.

7.4.2 Functional system evolutions

The previous modelling results have shown that the agent scenarios (in other words, use of different mental models) result in evolutionary pathways that show some large diversity in the number of organisations and bioenergy sources (electricity or biofuel) provided. This section explores in more detail how it is possible to compare and evaluate different network evolutions to each other in terms of sustainable development. Figure 7-23 shows the economic, social and environmental contributions of the nine different scenarios explored (where the x-axis shows the time in years and the y-axis shows the normalised values for each of the contributions). The three graphs in figure 7-23 provide an insight into the overall performance of a particular evolutionary pathway.



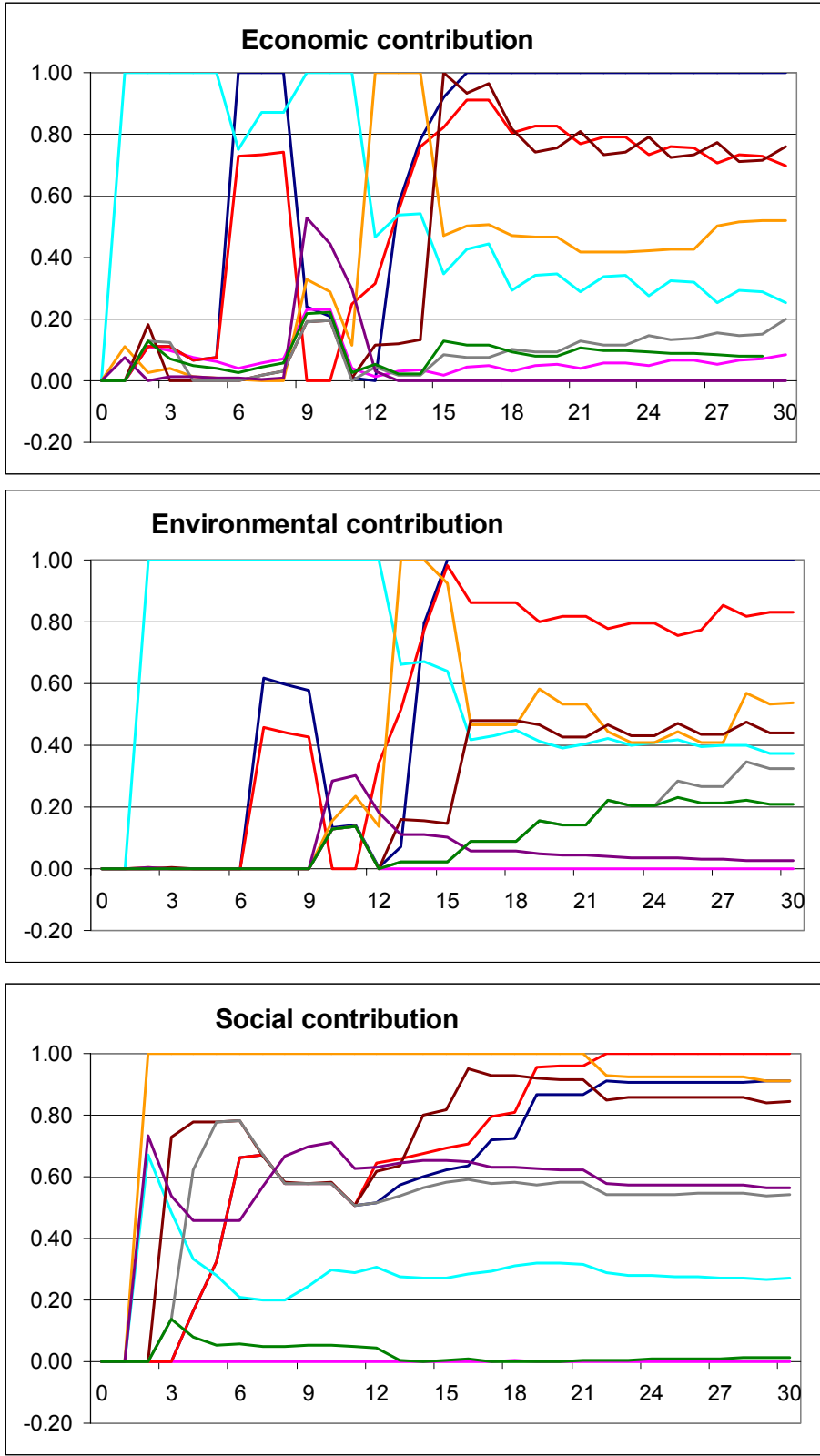


Figure 7- 23 Economic, social and environmental contribution of the different scenarios (legend on previous page)

relative other possible evolutionary pathways. Two general observations can be made on the basis of this analysis. Firstly, scenario 1 (red) and 3 (dark blue) perform well in the later stages of the network evolution. Both scenarios consist of a network in which bagasse is pelletised, electricity is produced locally (mainly on the basis of gasification) and where an independent power producer invests in enzymatic hydrolysis to use excess bagasse for the production of bioethanol in the latter stage of the network evolution. The second general observation that can be made is that scenario 2 (pink) and scenario (9) perform worse relative to the other scenarios in terms of social, economic and environmental contributions. Both scenarios do not have localised production of electricity by sugar mills and they produce relatively low energy outputs (5 and 9 PJ in year 30, respectively). The difference is that scenario 2 consists of centralised production of bioethanol, while scenario 9 consists of electricity production through cofiring.

The advantage of this evaluation is that it makes the dynamic performance of the industrial networks more explicit. For example, though scenario 4 (light blue line) does not perform particularly well at the later stages of the analysis, it performs best in terms of economic and environmental contribution at the initial stages of the system evolution. In other words, the contribution to sustainable development should be evaluated over the course of the evolution. An approach that only focuses on the total contribution over 30 years ignores the potential implications of these different pathways, and their associated value for the larger socio-economic system in which the system is operating. The second advantage of this analysis is that it takes into consideration a changing external environment. Since the price of oil and/or bagasse availability are different at different stages throughout the network evolution, the economic, environmental and social performance of an industrial network in one year cannot be compared to its performance at another year. In other words, the contribution of an industrial network is context dependent and this dependency needs to be considered in the overall network evaluation.

The next section will illustrate and analyse in more detail the structural features of the different network evolutions and their potential implications for sustainable development.

7.4.3 Structural system evolutions

Section 7.3.2 has already shown how different evolutionary pathways can be associated with different infrastructural developments and technologies. Furthermore, it was shown that even within a particular evolutionary pathway there can be different stages of network configurations. These different network configurations have an important impact on sustainable development and the evolution of the system as a whole. The results of the structural analysis will be presented in three parts. Firstly, a generic example will be provided on how structural indicators reflect structural changes within a network. The second part of this section will illustrate how structural analysis can be used to distinguish between different scenarios and their associated performance and the third part provides a generic reflection on the trade-offs between structural features and how this might relate to a) mental models and b) the evolutionary pathways of industrial networks. As in the previous sections, only selected examples will be discussed and an overview of all results can be found in appendix A4.

7.4.3.1 The relationship between structural indicators and network evolution

The structural indicators proposed in chapter 4 have been developed in an attempt to quantitatively reflect the performance of industrial networks in terms of sustainable development. This section explores the extent to which these indicators correlate with changes in system changes in the bioenergy network. As an example, figure 7-27 shows the structural changes in scenario 5. Figure 7-24 shows these structural changes in scenario 5. Subsequently, these structural features of this particular evolutionary pathway are compared to the numerical values of its structural performance in figure 7-25. Three important structural changes throughout the network evolution can be seen: 1) the investment in cofiring in year 9, 2) the investment in an ethanol production as well as local generation capacity at sugar mills and 3) the expansion of local generation capacity in sugar mills. Figure 7-24 shows the correlations between the energy output, the capital expenditure and the associated effects on the reduction of CO₂ emissions. Figure 7-24c shows the effects of localised electricity production on the number of households that receive electricity via mini-grids connected to sugar mills.

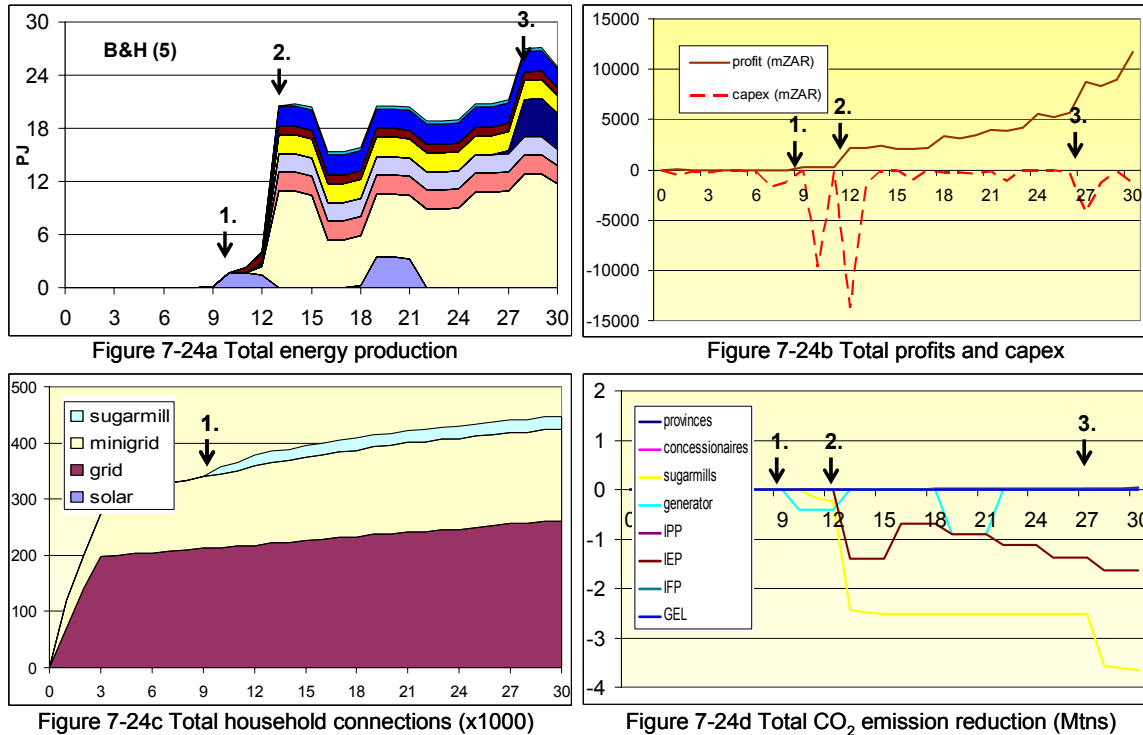


Figure 7- 24 The total energy production, capital investments and profits, household connections and CO₂ emission reduction in scenario 5

Figure 7-25 shows the structural performance criteria associated with these structural changes⁵⁶. Figure 7-25 shows that the structural indicators change when there are changes in the network configuration and/or use of resources. This indicates that structural changes in the industrial network evolution are accurately reflected in the indicators. The economic efficiency of the system increases (more economic value with less economic input), which correlates with increasing electricity and biofuel prices. The three year cycle of dips relates to the three year contract cycle, in which buyers of bagasse have to secure the bagasse and which is associated with a high influx of money. Large investments in the system reduce its effectiveness (since more value has been placed within the system to create the same output), although the increased energy production as a result of these investments increases the effectiveness. The resilience performance is high in the early stages of the network, when there is a large excess of pelletising capacity, however slowly diminishes as more electricity is produced.

⁵⁶ Four indicators are omitted (social effectiveness and efficiency and environmental effectiveness and efficiency), because their scale was too small to represent in conjunction with the other indicators. The full set of results is provided in appendix A4.

The social resilience of the network becomes negative, indicating that there is more electricity produced than the number of household connections available to deliver the electricity within the region. A small increase in economic and environmental resilience can be seen with additional investments in generating capacity (in year 27). However, the associated increase in electricity production reduces the social resilience of the system. The social adaptiveness of the system is fairly constant over the time frame of the analysis with a small increase when minigrids connected to sugar mills are introduced. The economic and environmental adaptiveness increases with an increased participation of sugar mills in the production of electricity and follows the pattern associated with the entrance and exit of the cofiring facility within the network.

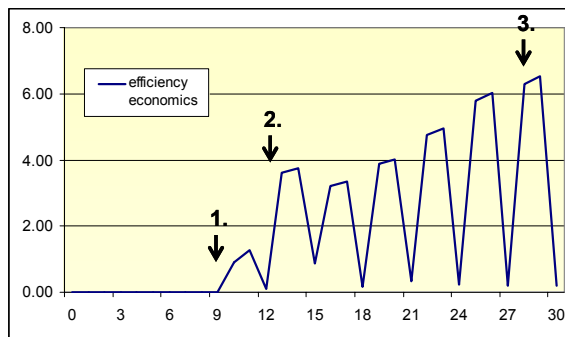


Figure 7-25a Efficiency

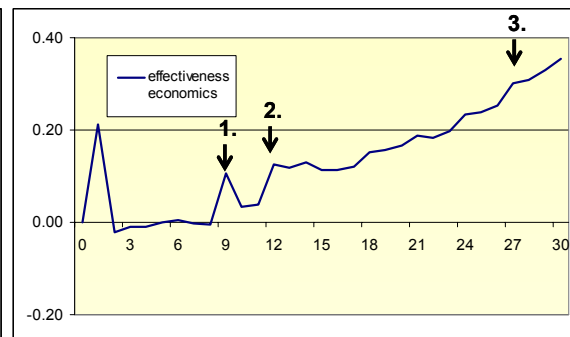


Figure 7-25b Effectiveness

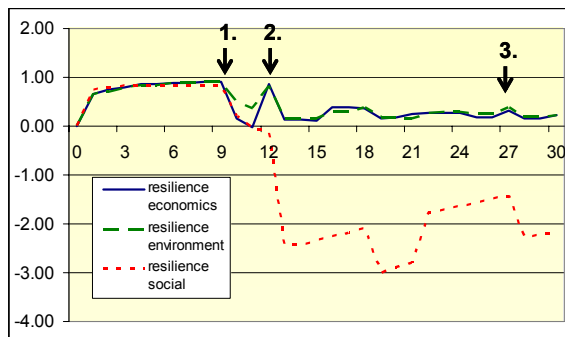


Figure 7-25c Resilience

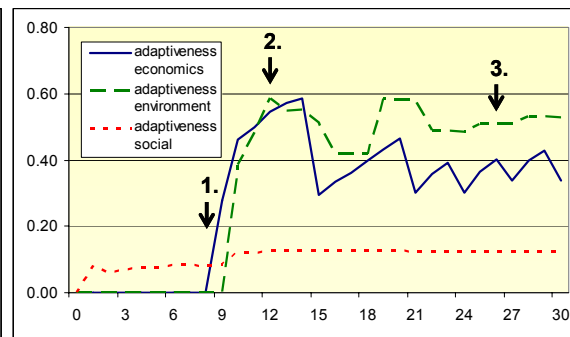


Figure 7-25d Adaptiveness

Figure 7- 25 Structural indicators associated with the network evolution of scenario 5

This example has demonstrated that the structural indicators suggested in chapter 4 are responsive to structural changes in the different network evolutions. The use of structural indicators has no added value for the analysis of a single evolutionary pathway, because structural changes are clear from observations. However, the next two sections will discuss in more detail how these quantitative indicators can be used to compare multiple network evolutions to each other and how they can assist in elucidating different trade-

offs between different performance indicators and between performances at different points in time throughout the network evolution.

7.4.3.2 Comparison of scenarios

In section 7.4.2, functional performances were used to reflect on the sustainable development of industrial networks. However, the functional performance of industrial networks is only part of their total impact on sustainable development. This can be illustrated on the basis of a comparison of scenario 3 and 6. Both scenarios have similar cumulative energy output (see figure 7-26). Previously, it has been shown that their contribution to economic and social performance profiles was also similar, when reported in terms of functional characteristics (see the red and brown line in figure 7-23 in section 7.4.1).

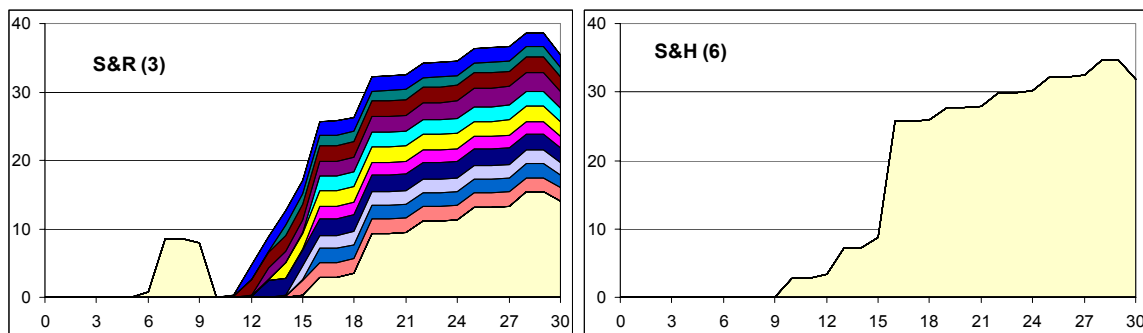


Figure 7- 26 Comparison of the total energy output (PJ) of scenario 3 and 6 over 30 years (similar legend as figure 7-14, 7-18 and 7-19)

However, it is clear from figure 7-26 that both networks have completely different network configurations; scenario 3 consist of 11 sugar mills and 1 ethanol producer, while scenario 6 consists of only one energy producer. Despite the clearly observable differences between these two evolutionary pathways, an evaluation on the basis of purely functional performance is insufficient to differentiate their characteristics. To reinforce this assertion, figure 7-27 and figure 7-28 show structural comparisons of these two scenarios in terms of their economic, environmental and social contributions to sustainable development.

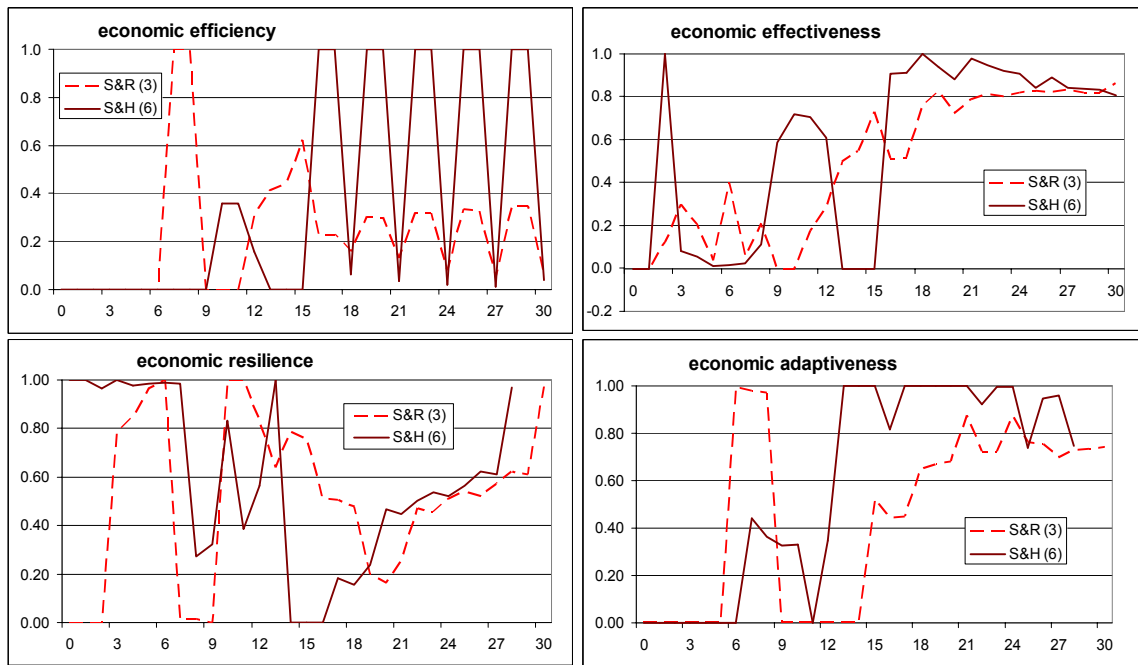


Figure 7- 27 Structural comparison of scenario 3 and 6

Again, figure 7-27 shows little difference between scenario 3 and 6 in terms of the structural performance, except for a higher economic efficiency of scenario 6⁵⁷. This means that the value economic created by scenario 6 relative to the economic value of bagasse used is higher than in scenario 3. The reason for this is the higher prices that can be obtained through selling bioethanol. However, for all the other structural indicators scenario 3 and 6 perform similarly. Both systems are effective and resilient and both systems have a high diversity in the number of organisations that contribute to the economic performance of the system (although the sugar mills do not produce electricity, they still contribute to the economic diversity of the system, because they have installed pelletisers and sell dried bagasse).

The real difference between the structural features of scenario 3 and 6 becomes evident in figure 7-28, which shows the comparison between the environmental and social

⁵⁷ The three-year cycle of high and low efficiency performance is related to the three year contracts that exist. The efficiency dips reflect the end of a contract period in which suppliers have to buy new contracts and new cashflows enter the market. This means that the economic efficiency of the system in those years drops (except for scenario 4 where there is no trade of bagasse and therefore no additional money flows into the market (reflected in a peak of economic efficiency in that particular scenario (see appendix A4)).

adaptiveness of both scenarios. Recall that adaptiveness is based on the level of diversity within the system. A higher degree of adaptiveness correlates with higher balance, more variety and higher disparity between the different elements that contribute to the environmental and social performance of the industrial network. The larger variety of organisations contributing to reductions in CO₂ emissions and the larger possibility for the creation of minigrids, both on the basis of engines and via sugar mills means that scenario 3 has a higher adaptiveness than scenario 6. Figure 7-28 allows for a quantitative comparison of this difference.

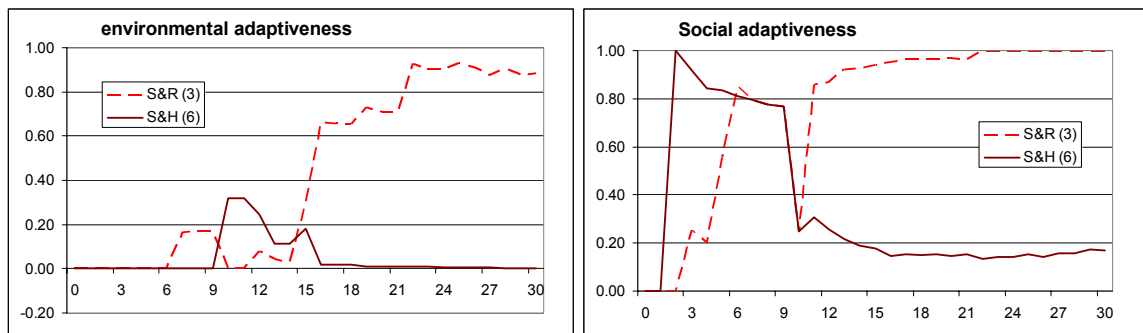


Figure 7- 28 Structural comparison of environmental and social adaptiveness of scenario 3 and 6

The advantage of the structural comparison is twofold. Firstly, it can be used to quantify observable differences between the structural features of a system and their potential contribution to sustainable development. Secondly, it provides a clearer understanding of how certain network configurations impact on the overall performance of the system.

7.4.3.3 Trade-offs within structural performance

Beside the use of structural comparison for the evaluation of different scenarios, the results also provide some generic insights on the potential trade-offs between structural performance of different network evolutions. Two trade-offs can be distinguished; 1) trade-offs between a particular performance within a particular network at different times throughout the network evolution and 2) trade-offs between different structural performance over the whole simulation.

The importance of intertemporal comparisons of industrial network contributions has already been discussed in section 4.3.2 and 4.4.1. In summary, inter-temporal comparison is important, because 1) the context in which networks operate changes all

the time, 2) there is interdependency between the different structural features of an industrial network, 3) normative values can change over time. Questions that can be addressed with this methodology include whether there is a clear trade-off between early stage performance and later stage performance and/or whether it is possible to compare network performances of a particular network at different stages throughout the network evolution. To address this question, figure 7-29 provides a comparison of scenario 4 and 7 and their associated absolute and relative performance indicators for economic adaptiveness.

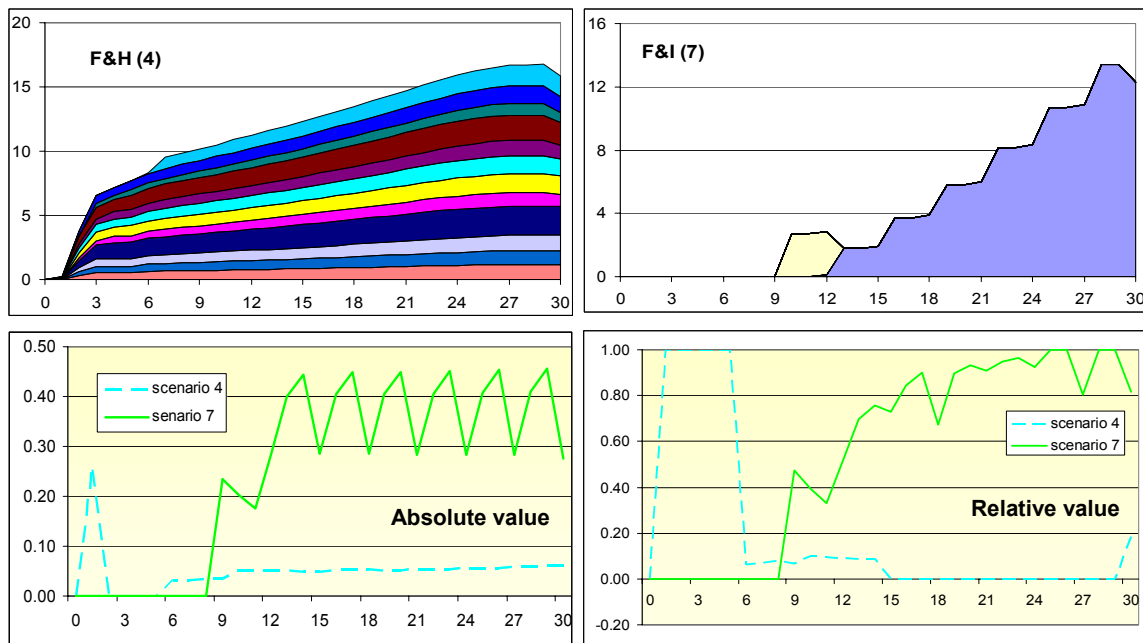


Figure 7- 29 Comparison of absolute and relative value of economic adaptiveness of scenario 4 and 7 (legend for 7-29a and 7-29b similar to figures 7-14, 7-18 and 7-19)

The results illustrate the importance of considering intertemporal trade-offs within the evaluation of industrial networks. The results for scenario 7 show that for some networks it is possible to compare the absolute performance of the network at different stages throughout the network evolution. However, scenario 4 is a clear example where this is not the case. Scenario 4 is the only evolutionary pathway which produces electricity and therefore economic benefits in the initial stages of the 30 year time frame⁵⁸. Although the

⁵⁸ The peak in absolute performance is associated with one particular year in which 1 sugar mill has invested in a pelletiser, 1 sugar mill has not invested at all and other sugar mills have invested in generation techniques. This results in a high diversity within the system. The year after that most sugar mills but one

economic adaptiveness of the network in absolute terms increases over time, the relative performance decreases. The implications of this observation are important: it means that decision makers should be cautious in comparing the performance of industrial networks at different stages of the network evolution without considering the context in which the networks operate.

The quantitative assessment of structural performance can be used to evaluate trade-offs between different structural performances. Questions that can be addressed are whether there are clear trade-offs between any of the four structural performance criteria; for example, does an increased resilience result in a decrease in effectiveness or does adaptiveness reduce the efficiency of a system? Figure 7-30 provides a comparison of scenario 2, 4 and 7 and their associated relative performances for resilience and effectiveness.

have losses, which means that the diversity for economic contribution decreases to almost 0. However, because there is no economic activity at all for any other network evolution, the relative performance of scenario 4 in terms of economic adaptiveness is highest.

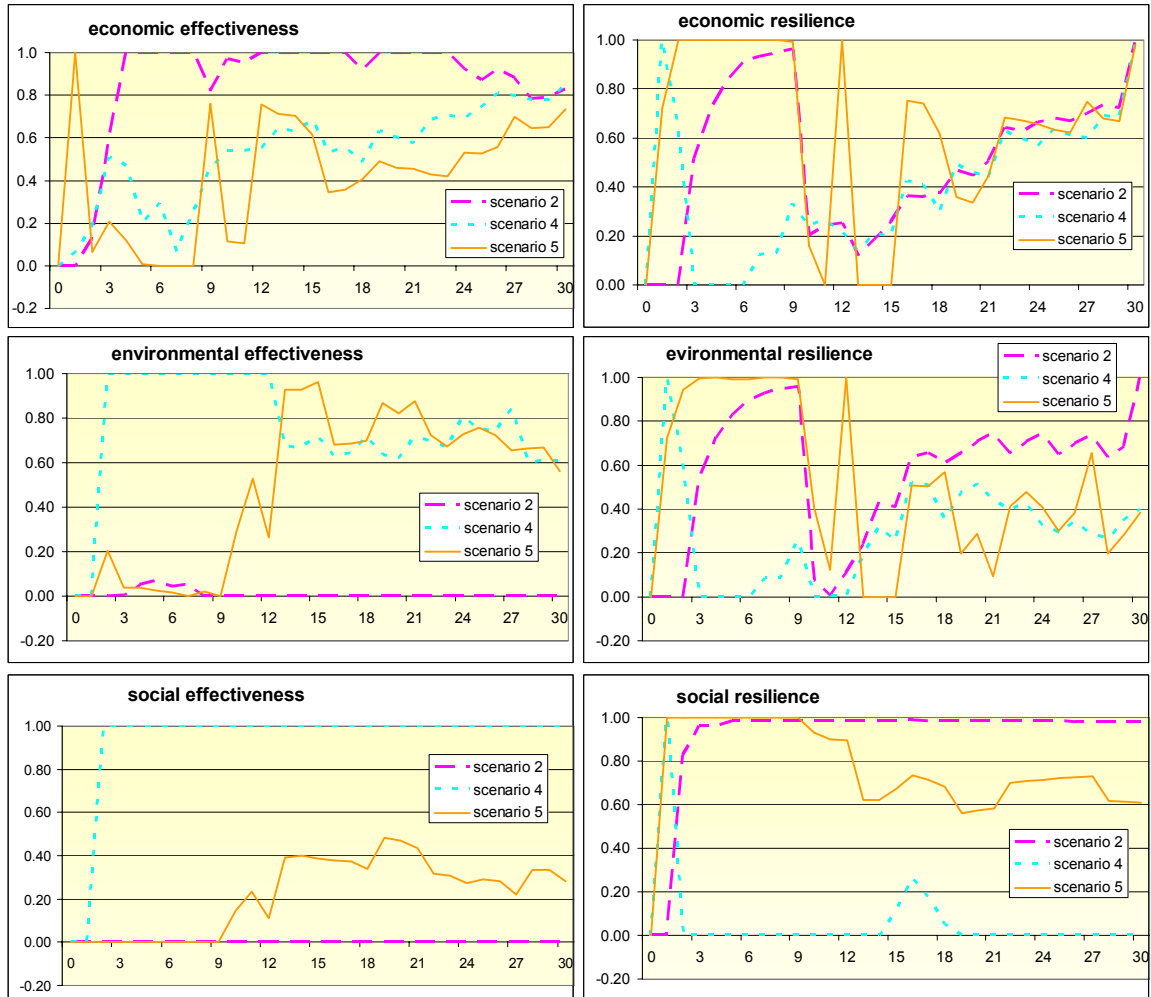


Figure 7- 30 Comparison of relative performance of effectiveness and resilience for scenario 2, 4 and 5

- F&R (1)
- B&R (2)
- S&R (3)
- F&H (4)
- B&H (5)
- S&H (6)
- F&I (7)
- B&I (8)
- S&I (9)

The results shown in figure 7-30 are not very surprising. An increase in resilience corresponds to a decrease in effectiveness and vice versa, since the indicators reflect the costs and improved redundancy associated with excess capacity within the system. However, the quantification of these trade-offs provide the decision maker with a clear picture of the extremes for both structural performance indicators and how these are related to structural characteristics of the industrial network.

The trade-offs are less clear for the other structural indicators within the network and there are no clear trends in any other trade-offs between either adaptiveness and

resilience, efficiency and effectiveness or effectiveness and adaptiveness. However, the results do seem to suggest that there is a clear distinction between the role of adaptiveness in the overall performance of industrial network evolutions.

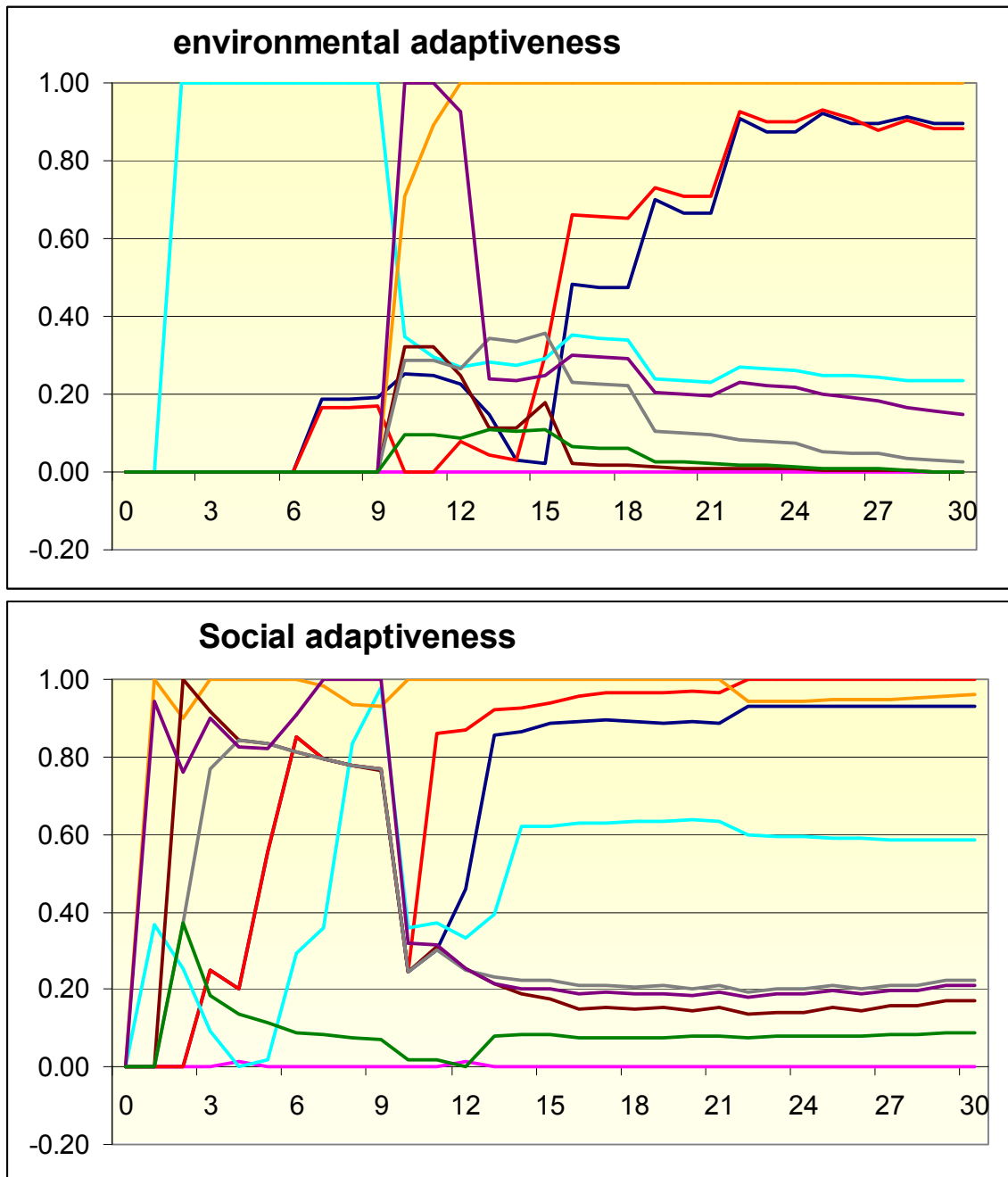


Figure 7- 31 Comparison of environmental and social adaptiveness of all scenarios (legend on previous page)

Figure 7-31 shows the environmental and social adaptiveness for the total set of scenarios. A clear distinction can be observed between scenario 1 (dark blue), 3 (red) and 5 (orange) and the other network evolutions. Each of these three scenarios consist of a network that 1) has a large capacity of pelletisers, 2) has localised production of electricity and 3) has either one or more independent producers on the market. The results of these three scenarios for efficiency, effectiveness and resilience do not show any extremes in terms of the results (they do not result in either the best or worst performance of any of the scenarios). In other words, these three networks are on average more robust over any of the other structural performance criteria. From these observations, it might be concluded that a high degree of adaptiveness (or diversity) enables the system to perform well over a larger range of performance criteria.

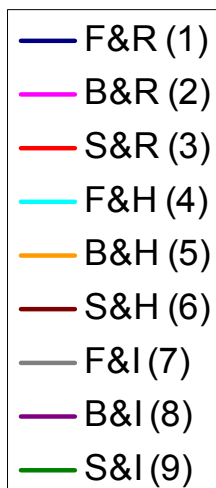
7.4.4 Overall system evolutions

The previous two sections have discussed the functional and structural performance indicators of industrial network evolutions separately. However, from a systems perspective functional and structural performance of industrial networks can compensate each other. For example, a system that has a low performance in terms of functional performance but a high performance in terms of structure might be as important for sustainable development as industrial networks that have high functional contributions but a vulnerable and inefficient structure. The trade-off between function and structure clearly depends on the context in which the network operates and on the objectives of the analysis. For example, in a region where there are direct and acute problems, a decision maker might prefer an industrial network that can provide immediate benefits regardless of the structural performance of the system. On the other hand, there might be decision situations in which an analyst prefers a system that provide a structural contribution over a longer period of time. In such decision situations, an industrial network with high structural performance might be preferred over a system that delivers immediate contributions.

The case study of the bioenergy network in KwaZulu-Natal resembles both situations. On the one hand, there is a set of stakeholders concerned with the immediate shortage of electricity generation capacity. From their perspective, a bioenergy network that can provide immediate contributions in terms of electricity production is preferred. On the other hand, there are stakeholders that are concerned with the long-term development of

the region and attracting and fostering local entrepreneurship and economic activities. From this perspective, a network that has the ability to provide economic, social and environmental benefits over a long-period of time is preferable, which requires a network that can adapt and grow over time. Explicit stakeholder engagement has not been conducted within this thesis and the value functions of stakeholders for any of the functional and structural performance criteria are unknown.

The application of the methodology for evaluation different bioenergy network evolutions is illustrated in this section. It is assumed that linear value functions exist for both the functional and structural performance criteria and for the economic, environmental and social contributions. Furthermore, equal weightings are assumed for both structure and function and for economic, environmental and social performance of the bioenergy network. Figure 7-32 shows the results on the basis of these assumptions.



The results show that, on the basis of the assumptions outlined in the previous paragraph, scenario 4 is preferred in terms of the short-term future. Scenario 4 represents a network that in an early stage starts producing electricity on the basis of combustion technologies and wet bagasse. Over the 30 years of analysis, neither pelletising techniques are introduced nor independent producers enter the network. On the other hand, scenario 1, 3 and 5 are preferred evolutionary pathways from a longer term perspective. These three scenarios all consist of a network where there is pelletising in an early stage of the network evolution and where both sugar mills and

an independent power producer operate within the network over 30 years. Furthermore, these results suggest that both scenario 2 and 9 perform worse in terms of the environmental and social contribution of the bioenergy network. These scenarios present different network evolutions, in which either bioethanol is produced on the basis of wet bagasse or where electricity is produced on the basis of dry bagasse. The similarity between these two scenarios is that both are dominated by a single player within the network.

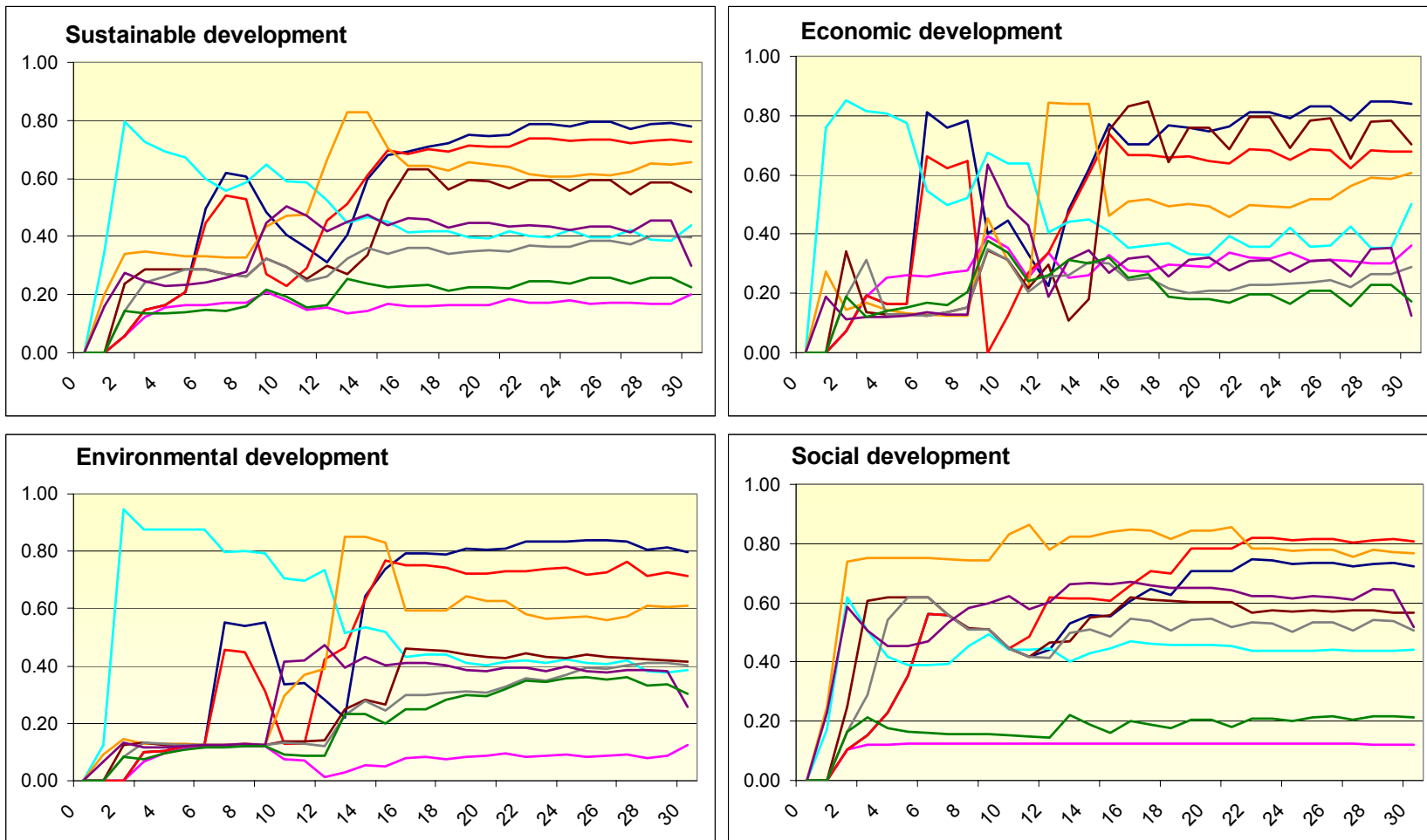


Figure 7- 32 The economic, environmental and social performance of the nine different network evolutions (legend on previous page)

From a methodological point of view, figure 7-32 addresses the three challenges that have been mentioned in chapter 4. It considers explicitly the openness of industrial networks by evaluating the performance of industrial networks relative to the context in which they operate. The results address both the functional and structural performance of industrial networks from a holistic perspective and it provides a clear picture of the dynamic features of industrial network evolutions.

7.4.5 Conclusion

This section has demonstrated the methodology developed to analyse sustainable development of bioenergy networks in a case study located in KwaZulu-Natal. The methodology is demonstrated for one particular context scenario in which the bioenergy network will operate, but the same methodology can be used to assess a set of context scenarios about the future. Three important conclusions can be drawn from this analysis. Firstly, the results support the assertion that 'mental models' of organisations are one of the most important determinants in the development of the bioenergy network. Other modelling runs, shown in appendix A4, show that different assumptions regarding growth rate parameters do impact on the evolution of the system, but exploring the uncertainty in the initial model conditions does not result in substantially different network evolutions. However, using different 'mental models' as the basis for a scenario allows you to explore the variety of potential network evolutions possible. Furthermore, the approach demonstrates how different evolutionary pathways are possible, regardless of the initial conditions and external context in which industrial networks operate. This has important implications for the current debate about sustainable development. The results show that it is not our current constraints that determine opportunities for sustainable development, but that within our current constraints a whole new set of opportunities can be created simply by changing our mental models about how to perceive and respond to the world.

The second conclusion is that both function and structure are important features of sustainable development and need to be considered for understanding the direction in which networks develop. The different structural indicators reflect the different structural features of evolutionary pathways and allow an analyst to differentiate between their performance. They also provide a clearer understanding on how particular network characteristics influence the direction of the network, how different network features can have similar effects on the network evolution (which cannot be observed without the

indicators) and how potential trade-offs are possible between the different network features, allowing the network to evolve to a better overall performance.

In terms of the technical evolution of bioenergy networks, the most important contribution of this analysis is that it has shown that in complex adaptive systems there is no preferred set of technologies or preferred structure that provides sustainable development. It has shown that sustainable development is related, foremost, to the evolution of the system and that it is the dynamic features of the system that are more important than the network performance at a particular point in time. It has also shown how particular sequences of structures and technology implementation can result in improved sustainable development. For the bioenergy network in Kwazulu-Natal, the results suggest that the most preferred evolution in terms of sustainable development is one in which an independent power producer enters the market and stimulates the introduction and development of pelletising technologies. An early entrance of bioethanol producers is less preferred, because production of bioethanol does not benefit from dried bagasse and therefore creates less incentive for sugar mills to invest in pelletising technologies. Furthermore, an early entrance of bioethanol producers defers the entrance of power producers into the network. However, in the long-run a bioenergy network is preferred that consists of both decentralised production of electricity and centralised production of biofuels. For infrastructural development, it is argued that those evolutionary pathways that focus on achieving a particular electrification threshold within a particular municipality are more preferred than those approaches that attempt to provide full electrification for each municipality.

7.5 Sustainable strategic decisions

The need to incorporate sustainable development as an integral part of the strategic decision making process of organisations receives increasing attention from not only industrial organisations themselves, but also from shareholders and customers. The problem is, however, that the adoption of practices stimulating sustainable development of individual activities not necessarily leads to sustainable development of the system (see for more details the discussion in chapter 4). Although there have been some attempts to develop policies that target sustainable development of total supply chains rather than individual organisations (VROM 2000 see for example), the results are still inconclusive.

One of the barriers for sustainable development of industrial networks is the social relationships between organisations and their positions within the network (Kempener 2003). Especially in industrial networks that are not governed by one dominant organisation, it is not foreseeable that competing organisations will engage in a collective MCDA exercises to 'design' optimal industrial network performance and negotiate the associated actions that each organisation should take. However, individual organisations can use MCDA techniques for their individual decision making processes if faced with multiple objectives and uncertainty. In particular, organisations can use MCDA methods to aid their decisions related to sustainable development. In this context, MCDA can be used to consider social and technical incommensurability of the different sustainability dimensions (Munda 2005:356). Social incommensurability refers to multiplicity of legitimate values in society. Although important for MCDA exercises that involve multiple stakeholders, social incommensurability is more difficult to take into consideration for individual organisations in an industrial network where the stakeholders might be competitors. Furthermore, in the context of industrial networks organisations are mainly interested in achieving their own objectives and, even if they would be interested in other people's values, would not know their values. Technical incommensurability comes from the multidimensional nature of sustainability issues. In particular, it refers to the issue in how far economic, ecological and social dimensions are substitutable. According to the degree of compensation allowed, weak or strong sustainability concepts can be operationalised (Polatidis, Haralambopoulos et al. 2006:187). Weak sustainability, in this context, refers to the view that natural resources can be substituted by man-made capital. It can be reflected in compensatory multi-criteria techniques, such as MAUT. Strong sustainability, on the other hand, reflects the view that some natural resources are critical to the regenerative or adaptive capacity of the earths' ecosystem and cannot be substituted by man-made capital (Munda 2005:974). Non-compensatory multi-criterion methods, such as outranking, reflect a view of strong sustainability.

Both methods, MAUT and outranking techniques (ELECTRE III), have been used to asses how sustainability considerations on an organisational level affect sustainable development of industrial network as a whole. Both tools have been popular instruments for aiding decision makers in strategic planning processes, especially in the context of

sustainable development (Kangas, Kangas et al. 2001; Buchanan and Vanderpooten 2007; Doukas, Andreas et al. 2007). In the case study, a set of models is developed in which organisations in the bioenergy network use MAUT and outranking techniques to make their investment decisions. In the context of this thesis, investment decisions are a choice between different technologies. It is this choice between which innovative technologies to adopt that is a key step towards progress in developing sustainable industrial systems (Doukas, Andreas et al. 2007:845). MAUT and ELECTRE III are used here to compare the consequences of agents' decision choices in terms of their economic, environmental and social implications. In MAUT, the decision maker uses an IRR-threshold to determine the economic feasibility of a technology. However, the decision maker also considers the environmental and social benefits of such investments and compensates the IRR-threshold accordingly. The weights used to compare the economic, social and environmental performance are provided in table 7-5. ELECTRE III provides the decision maker with a ranking of interventions (or investment decisions). 'Status quo' is included as an alternative whereby the organisation decides not to act. The organisations use the project that appears highest on the list. For organisations that can consider multiple investments simultaneously in different regions (ie local governments), they use the ranking to select projects according to their final ranking.

The weightings for evaluating the economic, environmental and social consequences of the organisations actions are elucidated using the Swing Weighting technique. The weightings are shown in table 7-5.

Table 7- 5 Weightings associated with the economic, environmental and social performance of organisations in the bioenergy network

Organisation	Econ. weighting	Envir. weighting	Social weighting
Generator	0.8	0.04	0.16
IPP/IEP/IFP	0.61	0.03	0.36
SM1	0.69	0.03	0.28
SM2	0.83	0.04	0.13
SM3	0.8	0.04	0.16
SM4	0.69	0.03	0.28
SM5	0.83	0.04	0.13
SM6	0.83	0.04	0.013
SM7	0.8	0.04	0.16
SM8	0.65	0.03	0.32
SM9	0.74	0.04	0.22
SM10	0.65	0.03	0.32
SM11	0.69	0.03	0.28
SM12	0.74	0.04	0.22

The weightings are different for each organisation, because they are located in different local governments and within different municipalities, which means that their decision to produce electricity can have different social consequences. Each organisation chooses the alternative (investment option) that provides the best localised solution in terms of the three criteria. The value functions that are used for each decision making process are linear, for demonstration purposes. ELECTRE III requires three additional pieces of information, which represent thresholds to differentiate between the consequences of decisions for organisations. The 'preference threshold' indicates whether the consequences of an alternative are distinctly preferred over another alternative and the 'indifference threshold' determines the range within which the decision maker cannot differentiate the consequences of two options. The 'threshold value' determines the absolute minimum that an alternative needs to achieve in any of the criteria and the credibility value determines whether the overall contribution of an alternative is distinctly better/worse than another alternative. This thesis adopts the values used by Kangas, Kangas et al. (2001) for strategic planning of natural resources. The preference threshold is 50% of the local range. In other words, differences more than 50% of a particular criteria range of variation are all weighted equal to 1 in the concordance

matrix⁵⁹. The indifference is 10% of the local range, meaning that differences less than 10% of the range of variation were considered indifferent. The threshold value is 75% of the local range and the credibility value is 15% (Kangas, Kangas et al. 2001:225).

- SM12
- SM11
- SM10
- SM9
- SM8
- SM7
- SM6
- SM5
- SM4
- SM3
- SM2
- SM1
- GEL
- IFP
- IEP
- IPP
- Generator

Subsequently, the agent-based modelling is tool is used to analyse whether the use of solely economic decision making (on the basis of methods such as cost-benefit analysis) versus MAUT or outranking substantially changes the sustainable development of industrial network as a whole. For example, organisations still use particular mental models to observe the world, but instead of their normal cognitive processes they use MAUT and ELECTRE III to decide upon investment decisions. Figure 7-33 and figure 7-34 illustrate the effects of organisations using MAUT on the development of industrial networks.

⁵⁹ The concordance and discordance matrix in the ELECTRE III procedure determine whether two alternatives can be distinguished from each other. The overall result from ELECTRE III is a ranking of projects.

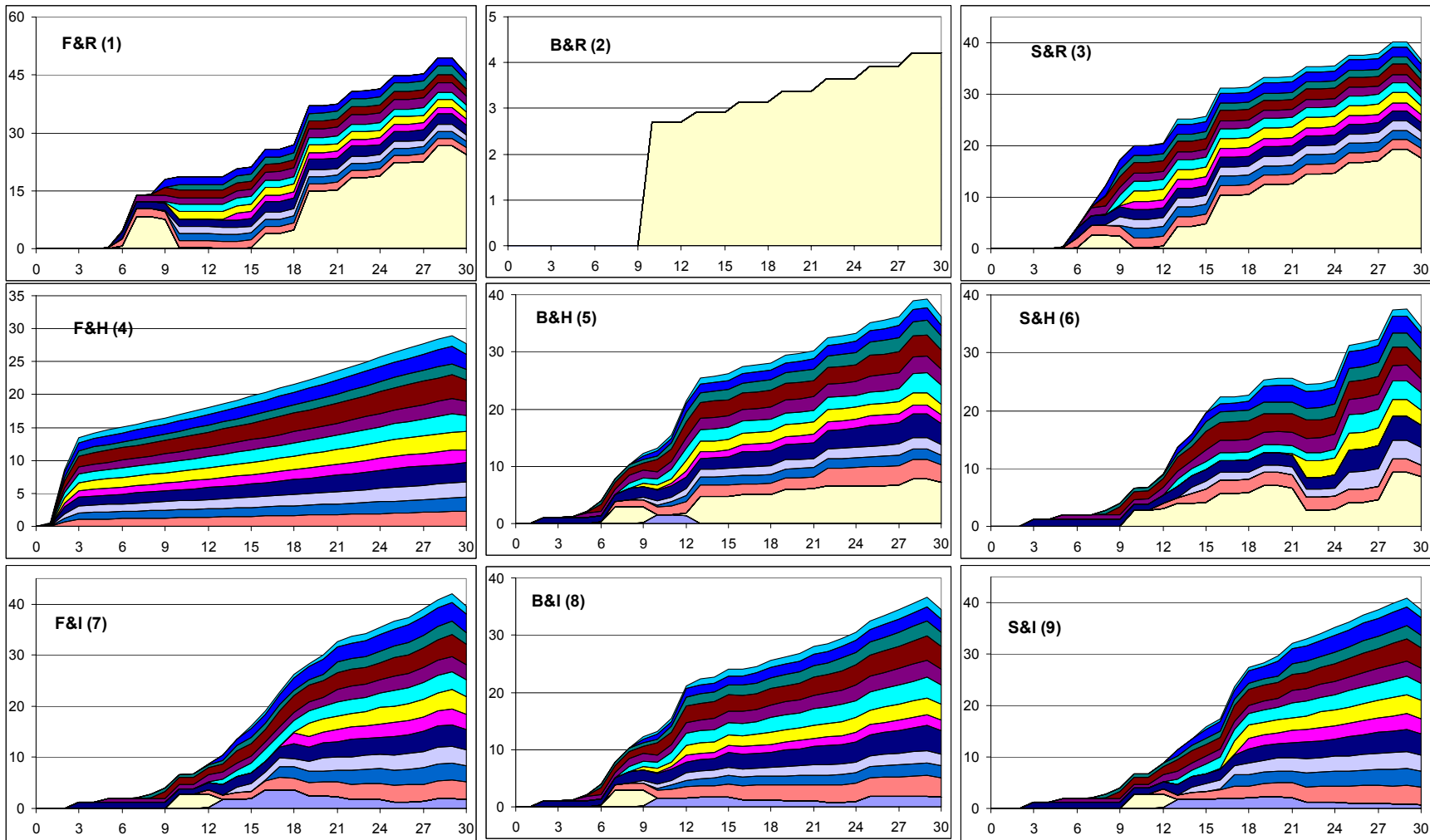


Figure 7- 33 Total energy production (in PJ) for the organisations using MAUT for strategic decisions over 30 years (legend on previous page)

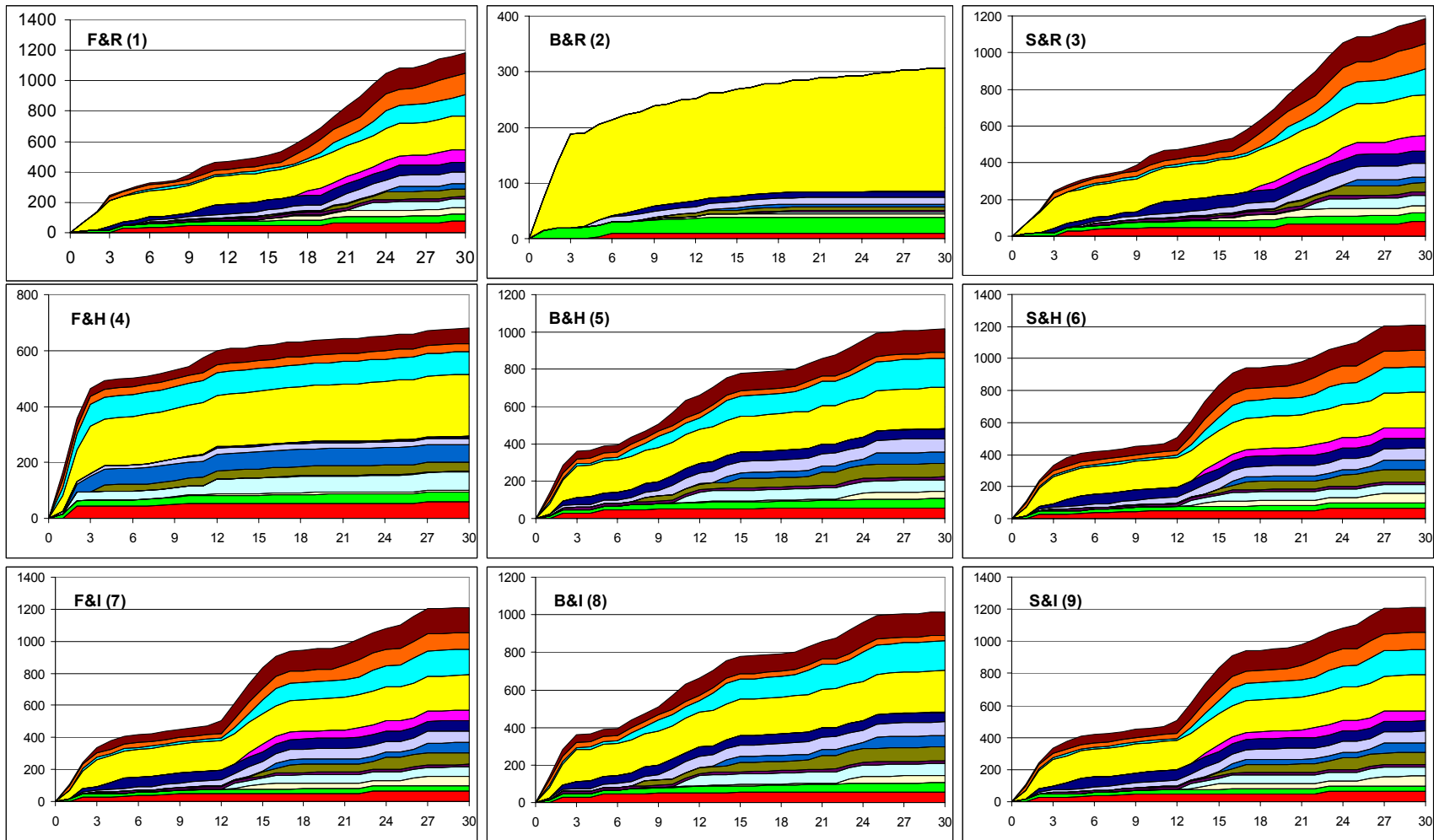


Figure 7- 34 Number of households (x 1000) connected by local governments and concessionaires using MAUT for making decisions on electrification activities over 30 years (legend on next page)



Both figures show that the use of MAUT has important impacts on the evolution of the bioenergy network (recall figures 7-14 and 7-15 in section 7.3.2, which showed the network evolutions with CBA). There are some scenarios where the use of MAUT has limited effect (see scenario 2). However, in general MAUT stimulates sugar mills to invest in electricity generation technologies much earlier throughout the evolution. The reason is that by using MAUT organisations base their decisions not only on the economic consequences, but also on environmental and social consequences of investments. Under these circumstances, positive environmental or social consequences compensate for less favourable economic consequences.

Another interesting observation is that despite all organisations use MAUT as their cognitive decision making process, the different mental representations still have an important effect on the network evolution. There are two reasons. Firstly, the indicators used to determine the economic consequences are different for different mental representations, which therefore affects the overall evaluation of an alternative. Secondly, the choice for partners is not based on an MAUT decision, which means that the choice of partner still has an important impact on the network evolution and performance. The reason that organisations do not employ MAUT for their partner choice is because environmental and social consequences of such choices are unknown.

The use of MAUT has in all but one scenario positive consequences for infrastructure development. Under most scenarios, the number of households connected is doubling. Figure 7-34 shows that the evolutionary pathway of electrification can differ depending on the mental models of the organisations. From this it can be concluded that the choice for different economic indicators is still an important aspects in the network evolution. There is not a single indicator, (profit calculations, payback time or IRR calculations in the case of concessionaires and connection costs, life cycle costs and maintenance costs in the case of local governments) that is clearly preferred over others. Instead, the model suggests that the most favourable network evolutions depend on the mix of perceptions about risk and the economic indicators employ by organisations.

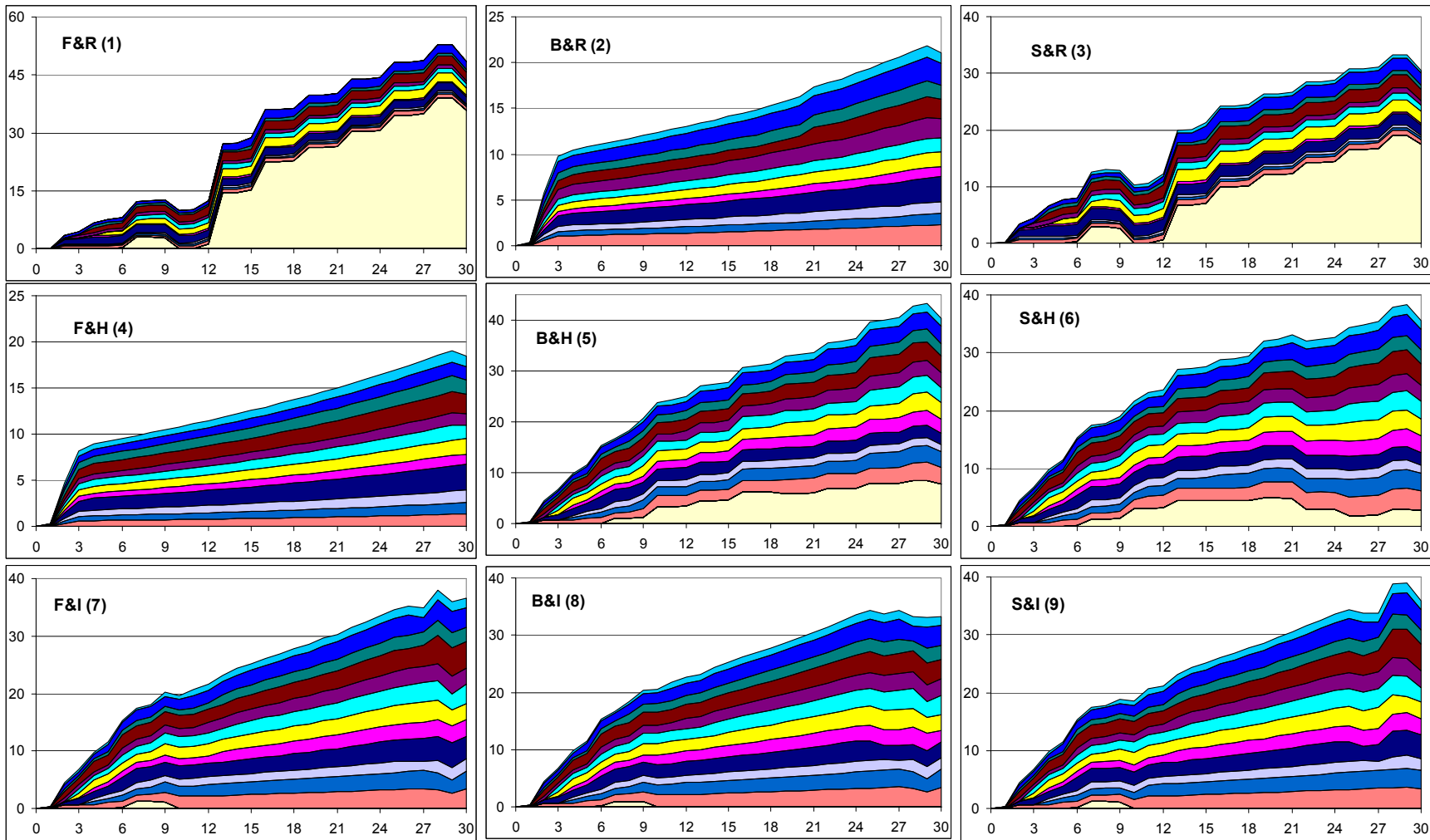


Figure 7- 35 Total energy production (in PJ) for the organisations using ELECTRE III for strategic decisions over 30 years

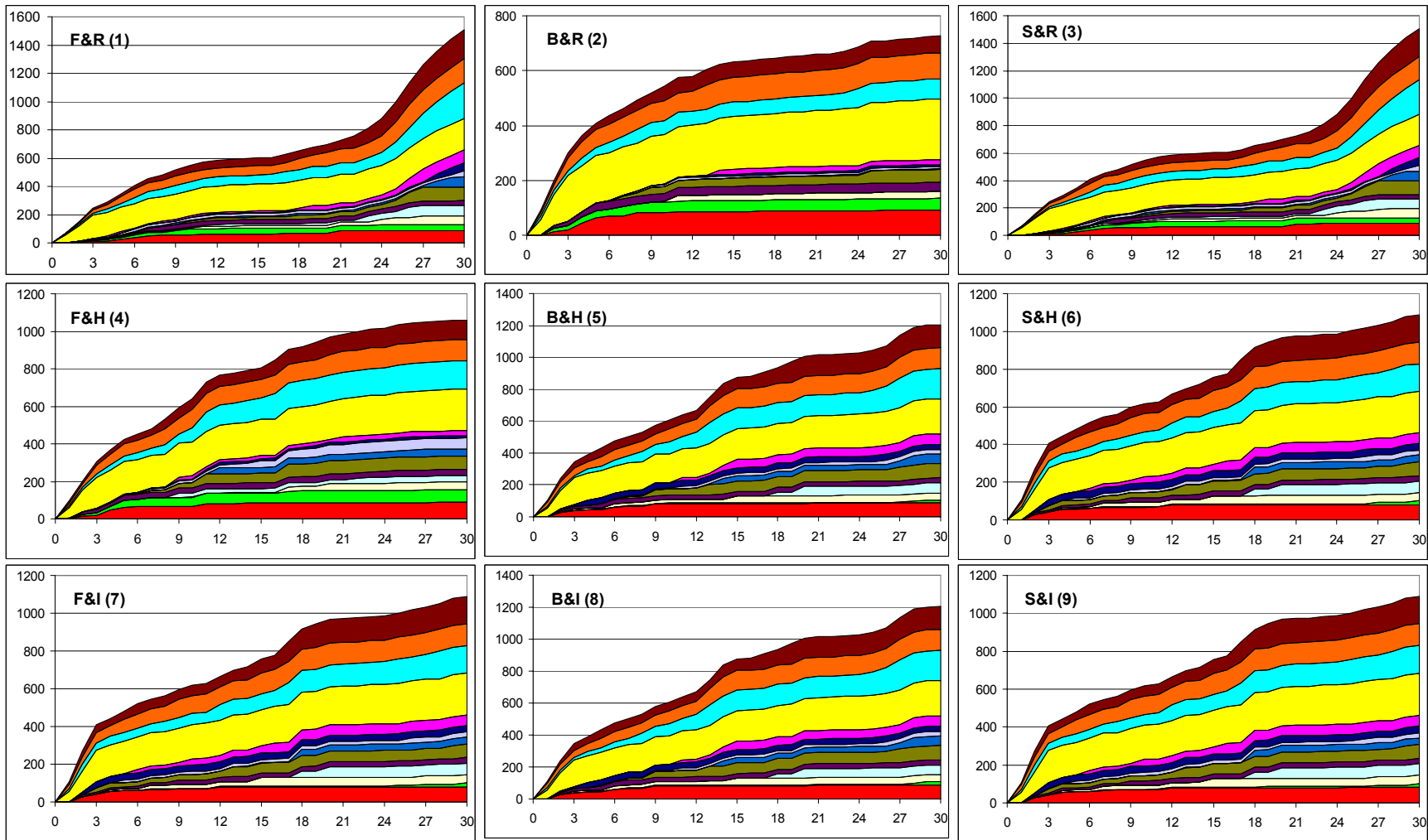


Figure 7- 36 Number of households (x 1000) connected by local governments and concessionaires using ELECTRE III for making decisions on electrification activities over 30 years

Figure 7-35 and 7-36 show the results for organisations employing ELECTRE III as their strategic decision making tool. In terms of generation, the use of ELECTRE III stimulates the electricity generation by sugar mills. However, the early adoption of generating technologies by the sugar mills also means that there is no emergence of centralised energy producers, because sugar mills use all the available bagasse themselves. Thus, although the use of ELECTRE III promotes local energy provision via sugar mills, it has also negative effects in that no additional generators or biofuel producers enter the network.

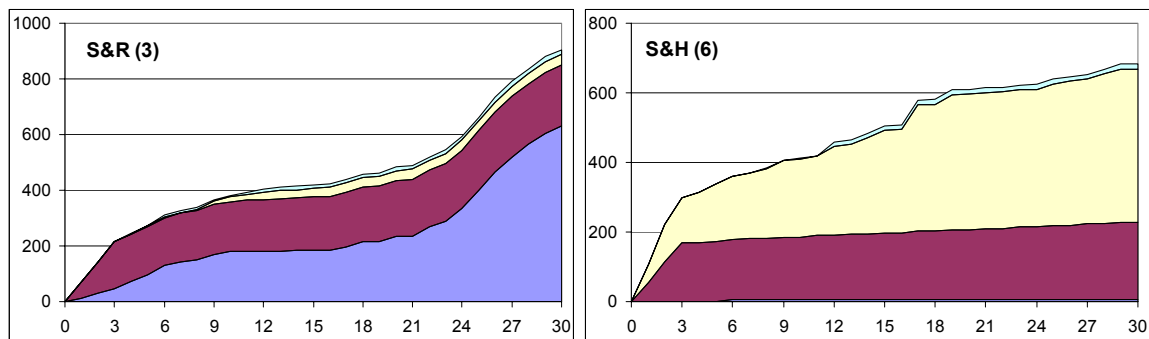


Figure 7- 37 Comparison of different infrastructure technologies employed by organisations using ELECTRE III for strategic decision making in scenario 3 and 6 (same legend as figure 7-33 and 7-35)

In terms of infrastructure development, there are also some interesting effects on the network evolution. Overall, the total number of households is higher than for the standard (ie economically rational) case or MAUT. However, in comparison there are some network evolutions where the rate of electrification is much lower in the initial phases of the evolution. The main reason is that choosing those municipalities that have lowest electrification rate can potentially provide greatest benefits in both environmental and social aspects, but requires large scale investments in engine capacity. These investments mean that local governments have to wait many years until they have enough financial capital for large-scale investment in engines. The trade-off between a slow initial uptake or a larger number of household connections at a later stage throughout the network evolution is an important question to address by stakeholders interested in stimulating sustainable development. The two different shapes of infrastructure development are connected to different preferences for technologies. In scenario 1 & 3, the economic evaluation on the basis of 'utility' favours the use of solar

systems, while the use of payback time or IRR favours minigrids (the risk perspective in scenario 2 diminishes this effect). Figure 7-37 shows a comparison between the uptake of different technologies between scenario 3 and scenario 6.

A comparison of the economic, environmental and social performance of the different strategic decision making tools (CBA, MAUT and OUTRANKING) is shown in figures 7.38 to 7.40. Not surprisingly, both MAUT and ELECTRE III increase the social performance of the bioenergy network in all cases through the introduction. However, under some scenarios MAUT is more beneficial, while ELECTRE III is in others. There seems to be no clear preference for either ELECTRE III or MAUT with respect to the different mental models, although it is clear that risk averse behaviour (scenario 2) is captured better by the ELECTRE III model. Depending on the analyst view on how urgent the need for electrification is within the region, one could argue that it is more important to have a better performance at the initial stages of the network evolution or that a network with better performance at the later stages is more preferred.

Despite concerns that considering social and environmental consequences requires 'internalisation of external costs', figure 7-39 shows that using MAUT or ELECTRE III in most cases is beneficial for the economic performance of the bioenergy network. Although individual performance of organisations might have reduced individual profits, the overall effects on the system are positive. However, it should be mentioned that these results are only valid in the context of the analyst's scenario, which in this case is a 'business as usual' scenario with steady growth in bagasse availability, electricity demand, oil and electricity prices. In other words, under conditions of a 'business as usual'-future, the introduction of MAUT or ELECTRE III have a positive effect on the economic development of a bioenergy network.

Finally, figure 7-40 shows the effects of introducing MAUT and ELECTRE III on the environmental performance of the bioenergy network. Again, the effects are mainly positive in comparison to standard decision making process. However, there is no clear advantage for using either MAUT or ELECTRE III. Scenario 2 is clearly improved by use of ELECTRE III, because it stimulated electricity production by sugar mills. However, scenario 4 shows that when sugar mills were already interested in electricity production, the use of ELECTRE III provides fewer benefits than introducing MAUT. This is mainly

due to lock-in effects, because with ELECTRE III sugar mills opt at an early stage for combustion or gasification techniques. Since investment in pelletisers do not have a direct social benefit to the sugar mill, extension of generating technology is preferred over new investments in pelletising capacity.

—	CBA
—	MAUT
—	OUTRANKING

Overall, it can be concluded that both MAUT and ELECTRE III have positive impacts on the economic, environmental and social contributions that a bioenergy can make. This section, however, has not discussed in detail the consequences of MAUT and ELECTRE III on the structural features of the system; efficiency, effectiveness, resilience and adaptiveness. An overall evaluation will take place in section 7.7.

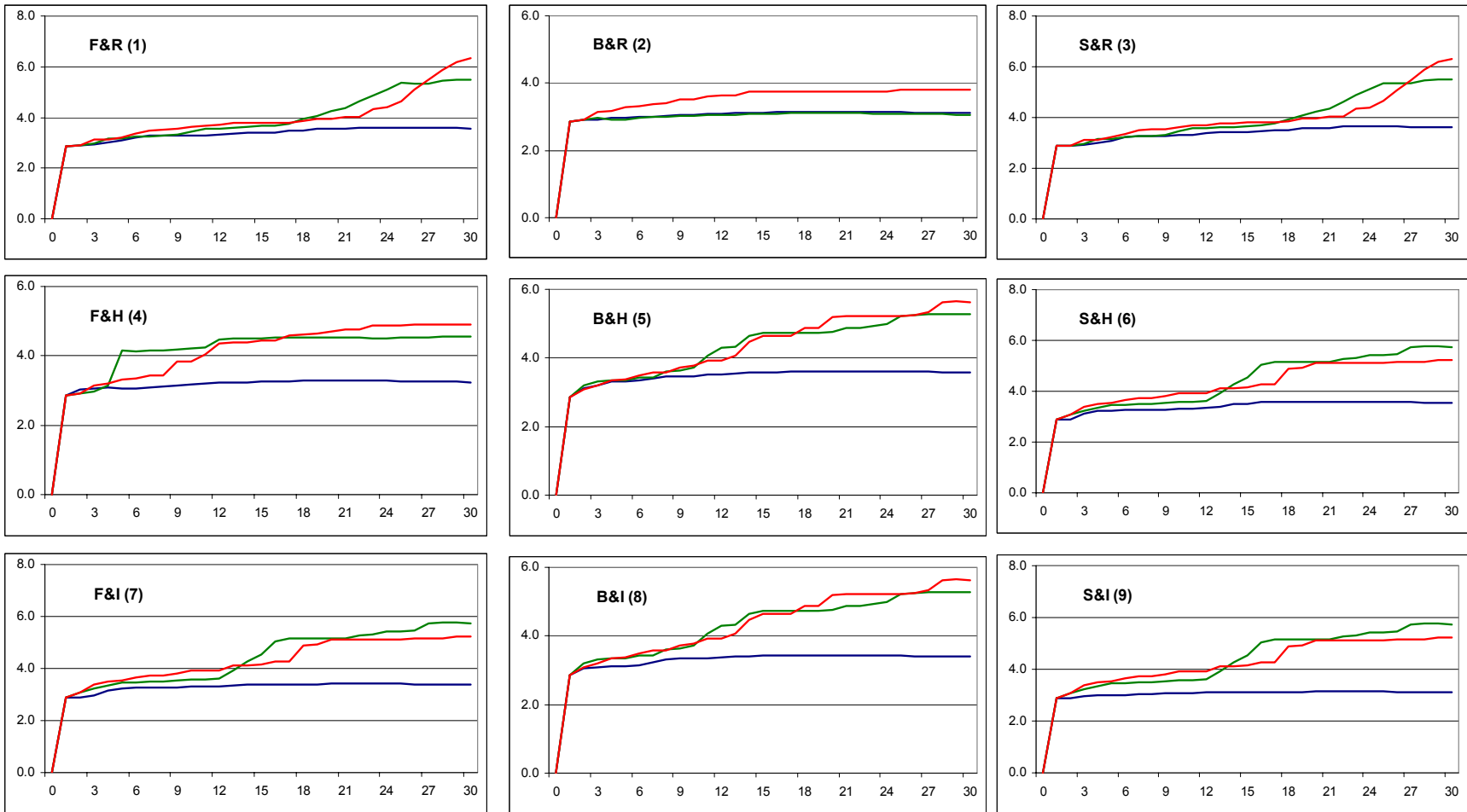


Figure 7- 38 Comparison of the effects of MAUT and ELECTRE III on social performance of bioenergy network over 30 years (legend on previous page)

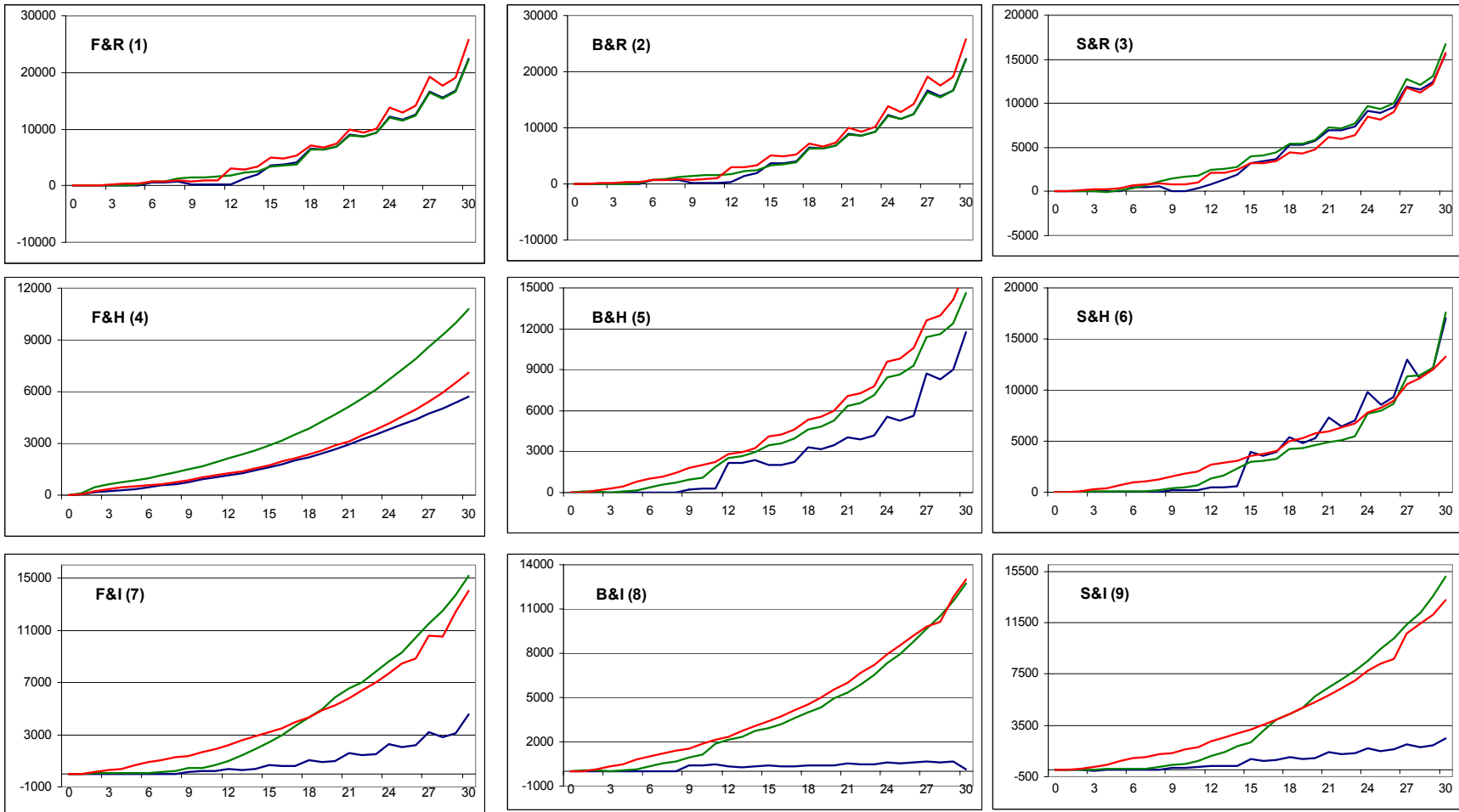


Figure 7- 39 Comparison of the effects of MAUT and ELECTRE III on economic performance (in mZAR) of bioenergy network over 30 years (legend on previous page)

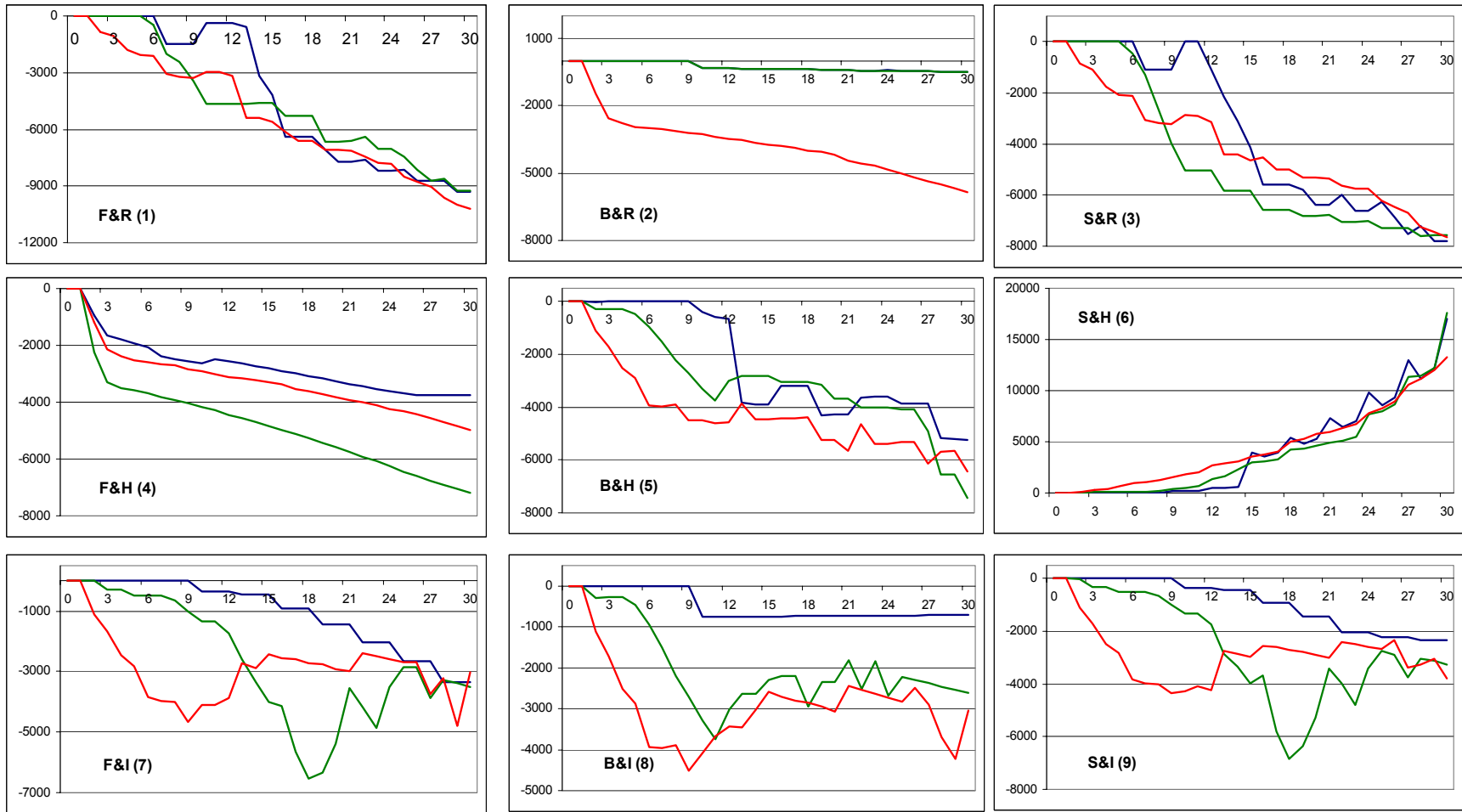


Figure 7- 40 Comparison of the effects of MAUT and ELECTRE III on environmental performance (in kTonnes) of bioenergy network over 30 years (legend on previous page)

7.6 Government interventions and sustainable development

In 2002, the South African government set a renewable energy target of an annual green electricity production of 10 TWh by 2013 and a biofuel target of 3.5% in 2012⁶⁰. At the moment, these targets have not been achieved although the expectations are that it will be possible by employing biomass as a renewable energy source. Currently, there are a number of price instruments in place for the production of biofuels in the form of tax exemptions (ranging from 40% to 100% depending on the scale of the biofuel production facility). These existing policy instruments already form part of the model developed in this thesis (see appendix A1). However, the production of green electricity is not supported yet and it is possible that the SA government may employ price instruments to stimulate the production of green electricity. Such price instruments are already in place in many other countries and states, where there exists a rebate for the production of green electricity. These rebates often are as high as 40% of the market price.

The green electricity target is not the only objective of the South African government that affects the future of the biomass energy network. The SA government has also expressed its interests in liberalising the market allowing other electricity generators to enter the network. Currently, financial instruments are already in place whereby potential electricity generators can apply for investment grants. These grants, together with potential price instruments, can play a very determining role in the future development of the biomass energy network. Therefore, the following interventions are suggested:

- a. The SA government does not develop any additional policy instruments.
- b. The SA government installs price instruments with a 20% rebate on market prices for electricity. These instruments will be in place until the current green electricity target (10 TWh) is met.
- c. The SA government installs investments instruments that provide up to 20% off current capital investment costs of new electricity generators. These instruments will be in place until the current green electricity target (10TWh) is met.

⁶⁰ This target is recently adjust downward to 2.5%.

- d. The SA government sets a higher target for green electricity (10% of total need in region). It uses price instruments that progressively increase and give up to 50% rebate on market prices for electricity to achieve this target.
- e. The SA government sets a relative target for green electricity (10 % of total need in region). It uses investment instruments that progressively increase up to 50% rebate on current investment costs for new electricity generators.
- f. The SA government reduces the tax rates on profits made from organisations operating in the bioenergy network from 35% (current rate) to 20%.

Intervention A forms the basis for the modelling results in section 7.3, which simulates the results for the network evolution with the current government policies in place (tax return for biodiesel and bioethanol). The government interventions explored in this section are not in place yet. For illustration purposes, this chapter will briefly illustrate the results of introducing the government interventions D, E and F. Other modelling results are shown in appendix A4.

- SM12
- SM11
- SM10
- SM9
- SM8
- SM7
- SM6
- SM5
- SM4
- SM3
- SM2
- SM1
- GEL
- IFP
- IEP
- IPP
- Generator

Figure 7-41, figure 7-42 and figure 7-43 show the total energy generation in the bioenergy network for three different government interventions. Contrary to the effect of strategic interventions, policy interventions do not necessarily stimulate participation of sugar mills in the bioenergy evolution. Under agent scenarios 1 to 4, policy interventions have limited or negative effects on the network evolution. Both price and investment subsidies stimulate large scale production of bioethanol production plant in the initial stages of the network evolution, because all sugar mills invest in pelletisers. The taxes and investment subsidies have a direct positive impact on the decision to invest in pelletisers, while price subsidy stimulate pelletising through an indirect effect. A price subsidy for electricity production raises the value that independent power producers and an electricity generator are willing to pay for bagasse, which has a positive impact on the sugar mills to invest in pelletisation. However, when price subsidies and investment

subsidies cease to exist, the use of bagasse is not so profitable anymore and the bioethanol producer is not willing to pay a premium price for bagasse anymore. This results in a network with a large unused capacity for bioethanol production.

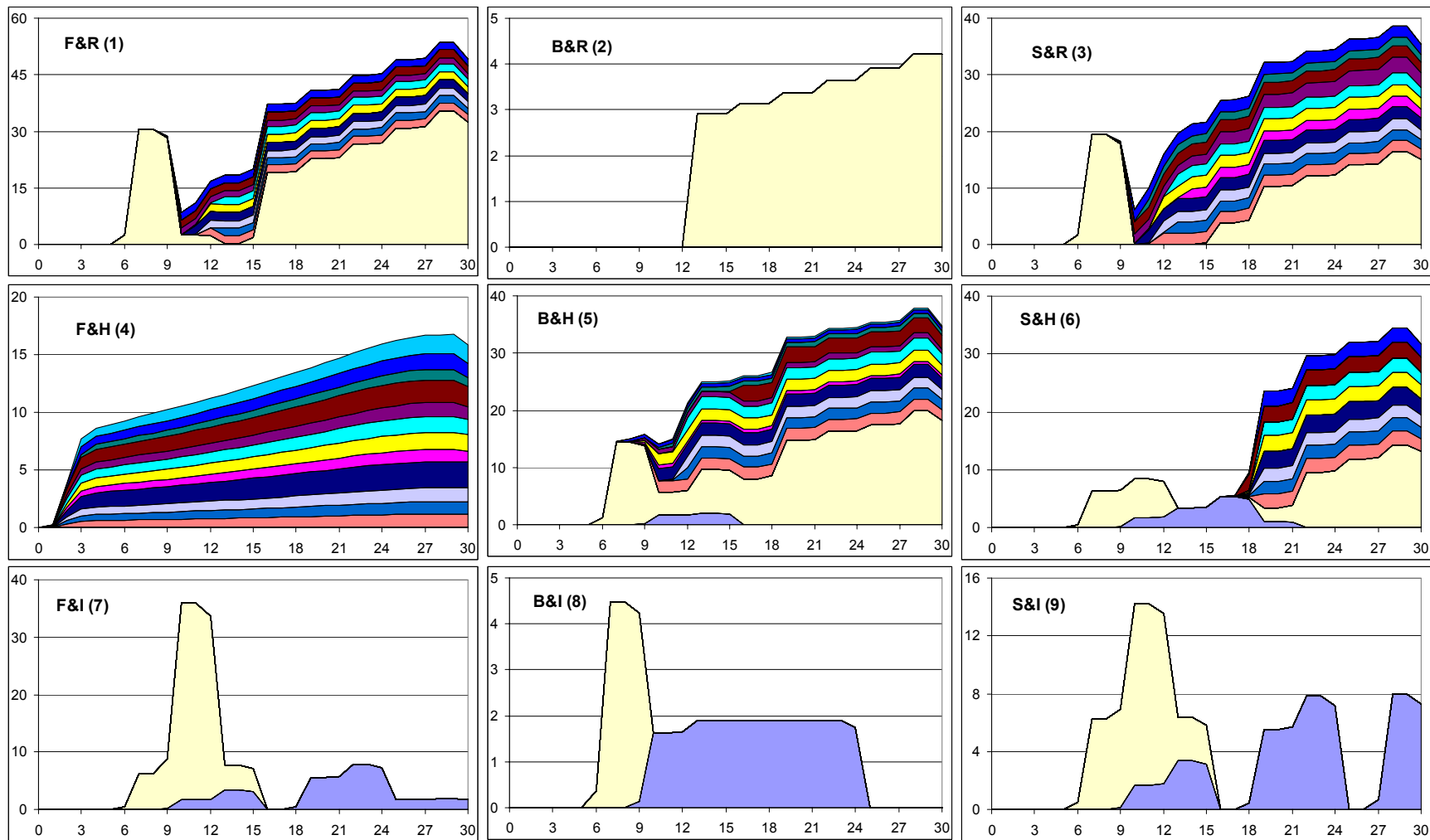


Figure 7- 41 Total energy production (in PJ) for the organisations in the bioenergy network with the introduction of price subsidies of 20% until the government target of 10 TWh is reached (legend on previous page)

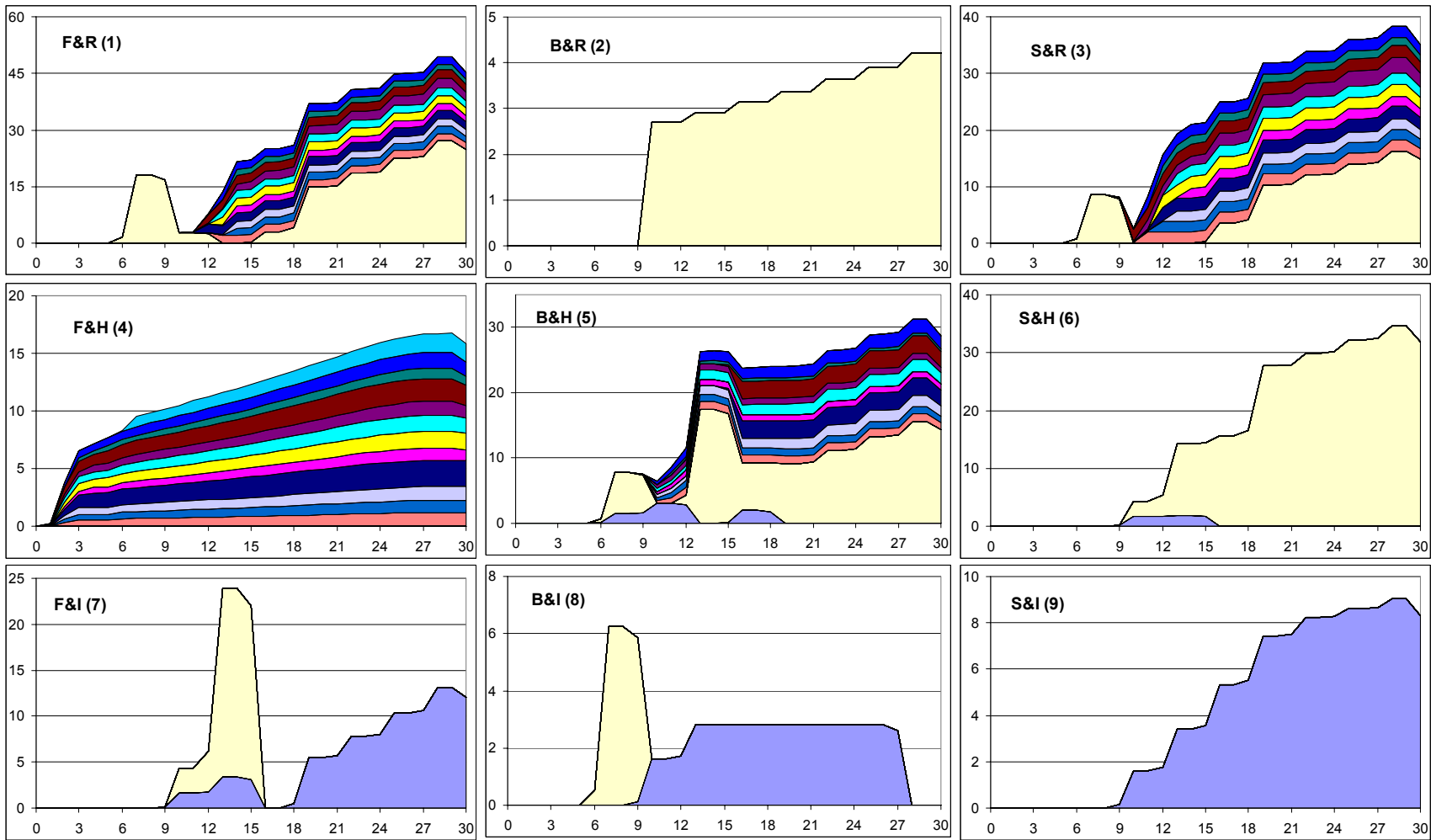


Figure 7- 42 Total energy production (in PJ) for the organisations in the bioenergy network with the introduction of investment subsidies of 20% until the government target of 10 TWh is reached (legend on previous page)

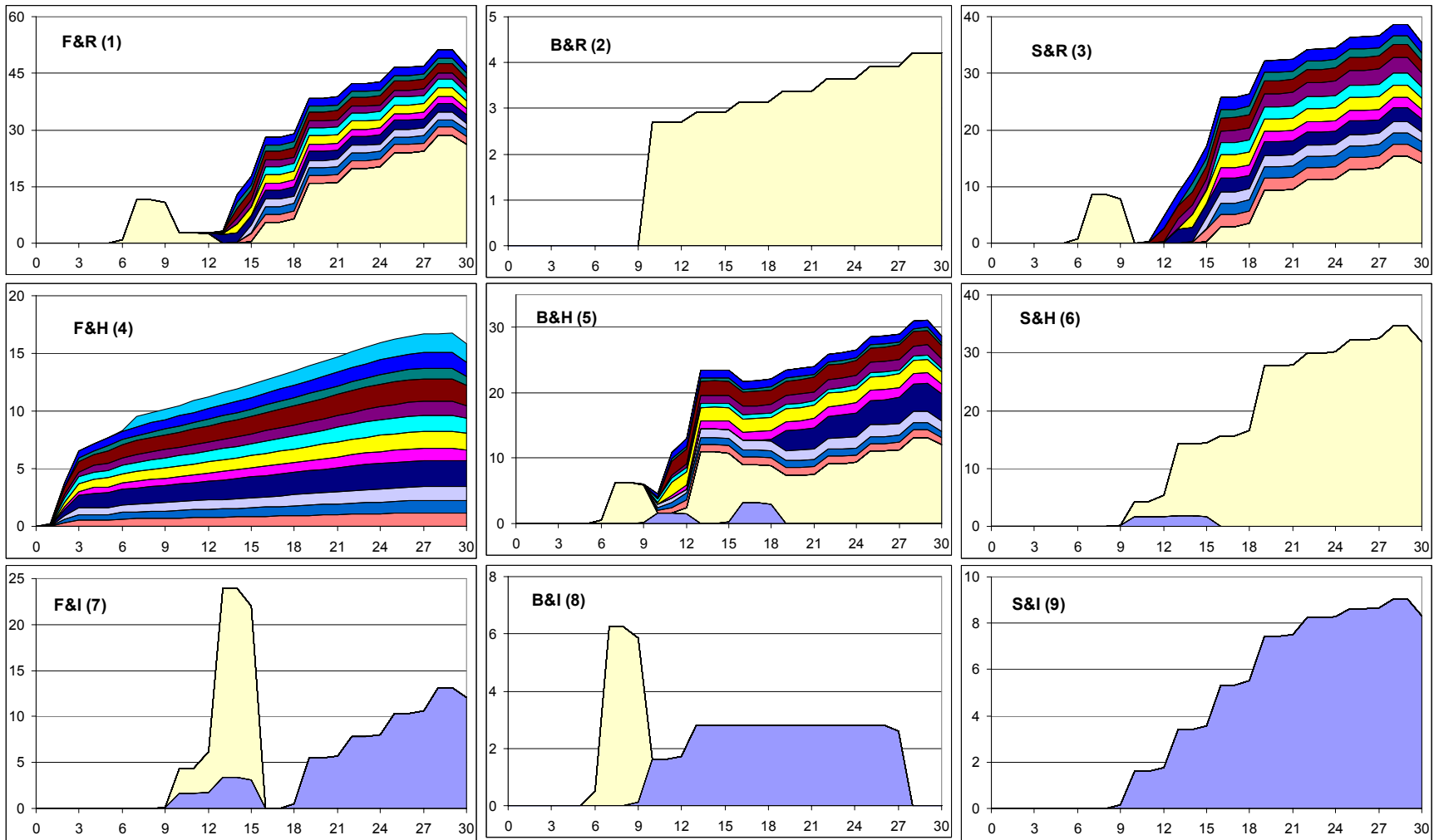


Figure 7- 43 Total energy production (in PJ) for the organisations in the bioenergy network with the introduction of tax reductions of 20% (legend on previous page)

On the other hand, there are also scenarios (ie agent scenario 5) that are positively affected by the introduction of policy interventions. In this scenario, the total energy production increases from around 24 PJ p.a. to 30-35 PJ p.a., mainly because of the increased incentives for pelletisation. Scenario 7 & 8 (and scenario 9 under the price subsidy) are also affected by the introduction of temporal policy interventions. However, they are affected throughout the rest of their evolution, because of the development of a market for dry bagasse. Figure 7-44 shows the price development of dry bagasse.

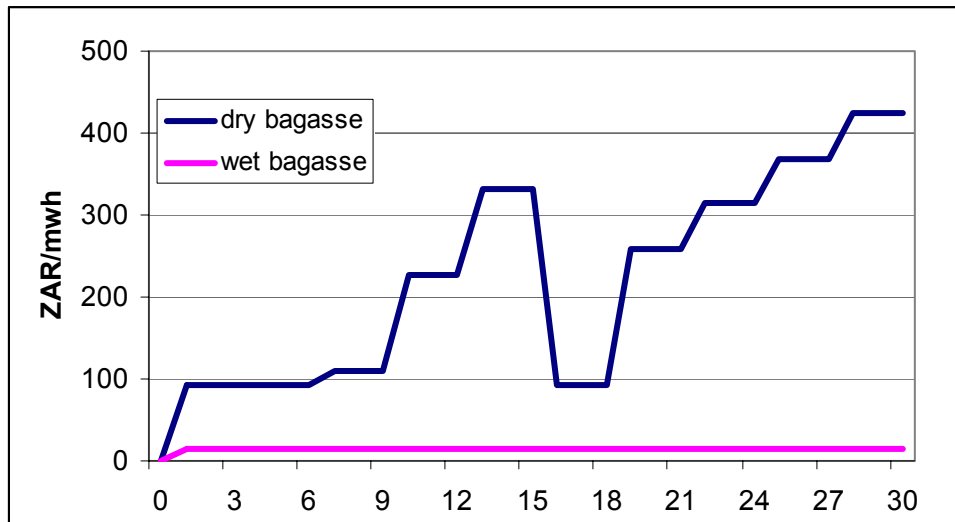


Figure 7- 44 Price development of both dry and wet bagasse in scenario 7 under price subsidies

The price and investment subsidies stimulate the development of pelletisation capacity. However, when the policy instruments cease to exist (around year 15), there is a large market for pelletisation with expectations for a reasonable price for their bagasse. However, simultaneously the independent power producers can offer less money for the bagasse and the price crashes (between year 15 and 18). In the subsequent years, the generator is able to pay a higher price than the ethanol producer, but only to a limited number of sugar industries. This means that there is a large excess of pelletisation capacity available without sufficient buyers of bagasse that can afford the price.

Figure 7-45 to 7-48 discuss the effects of policy interventions on the financial position of the government (7-45) and the overall effects on the economic, environmental and social performance of the network.

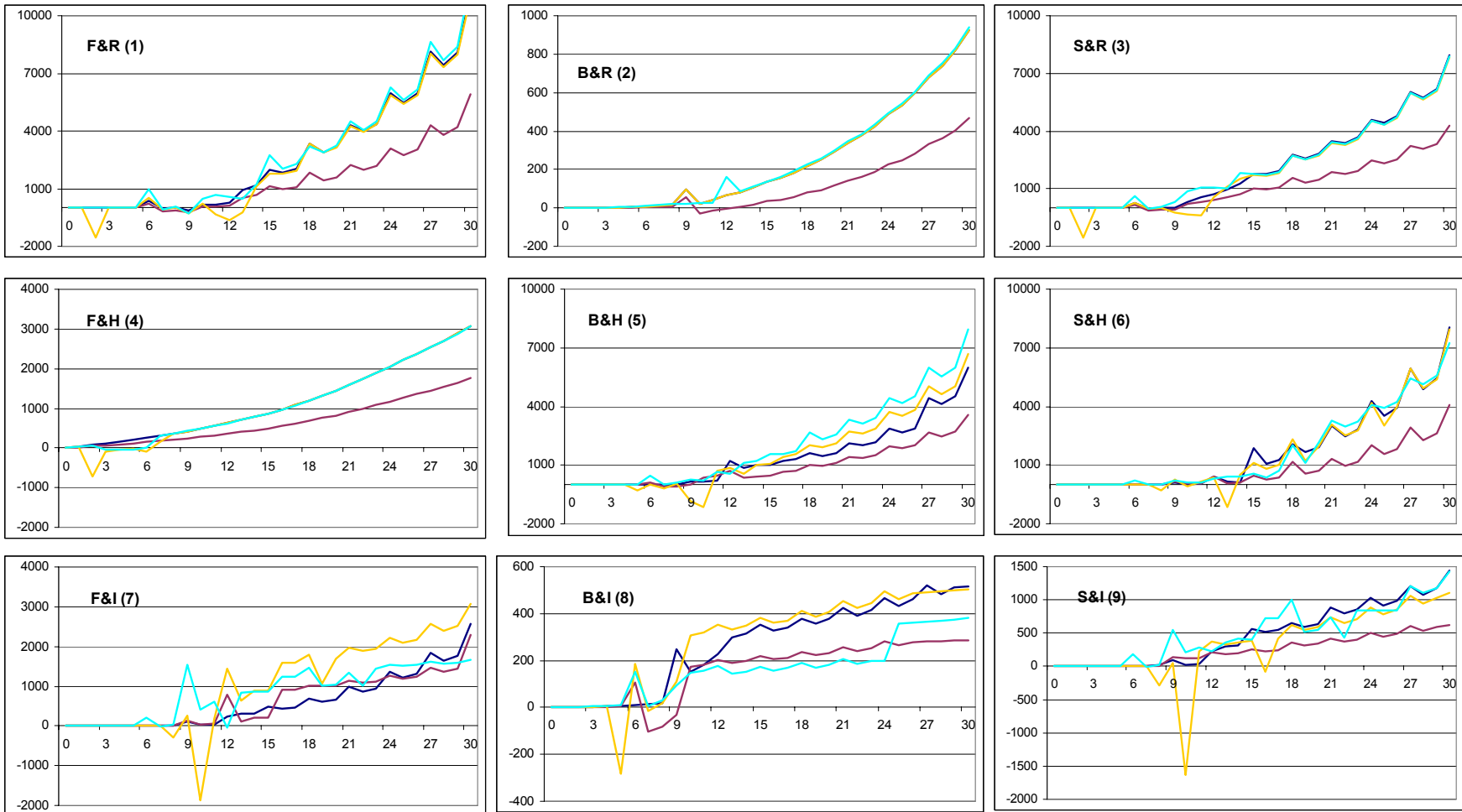


Figure 7- 45 Comparison of the total tax revenue minus subsidy expenditures (in mZAR) by the government under the three different government interventions to stimulate the bioenergy network (legend on next page)

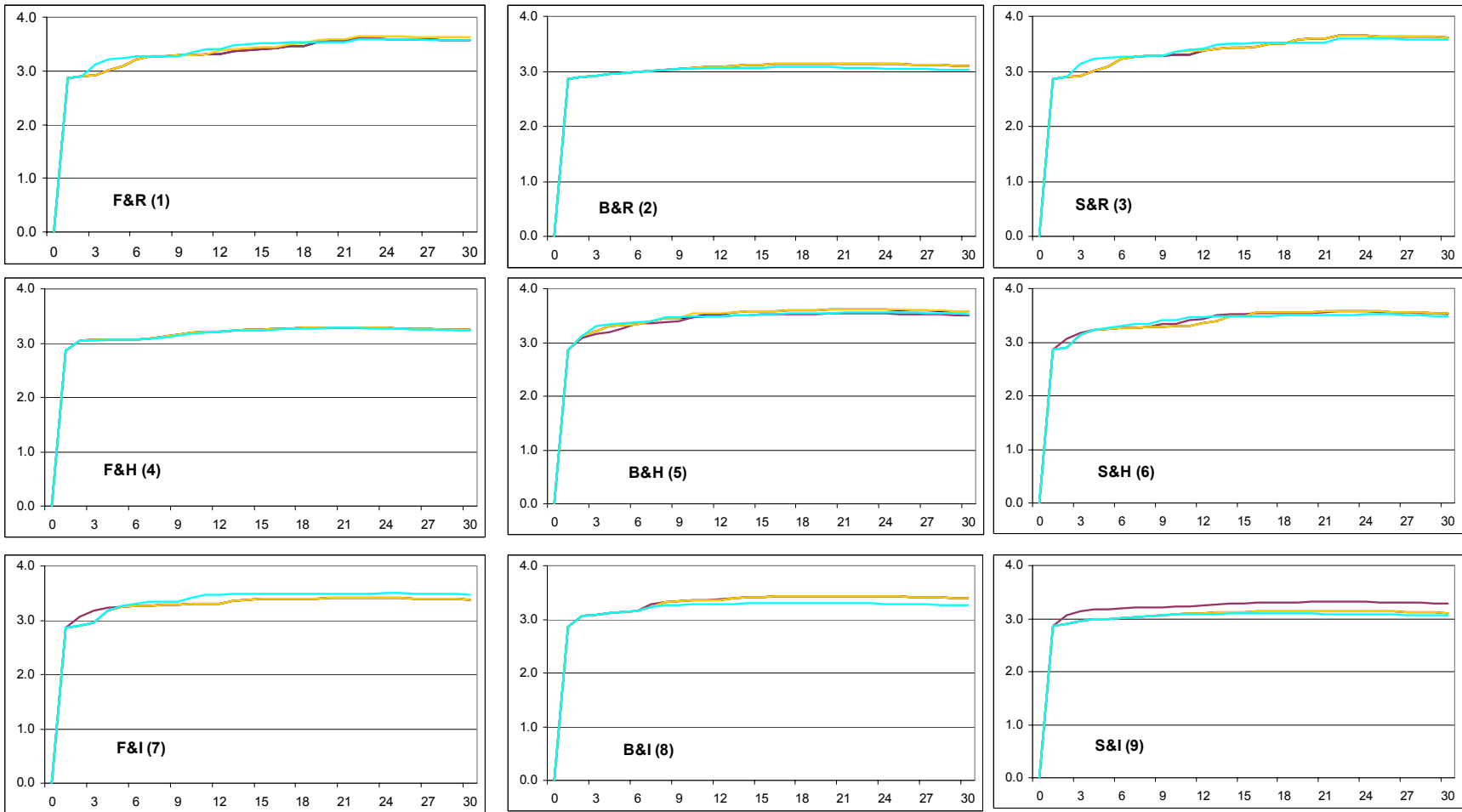


Figure 7- 46 Comparison of the effects of different government interventions on the social performance of bioenergy network over 30 years (legend on next page)

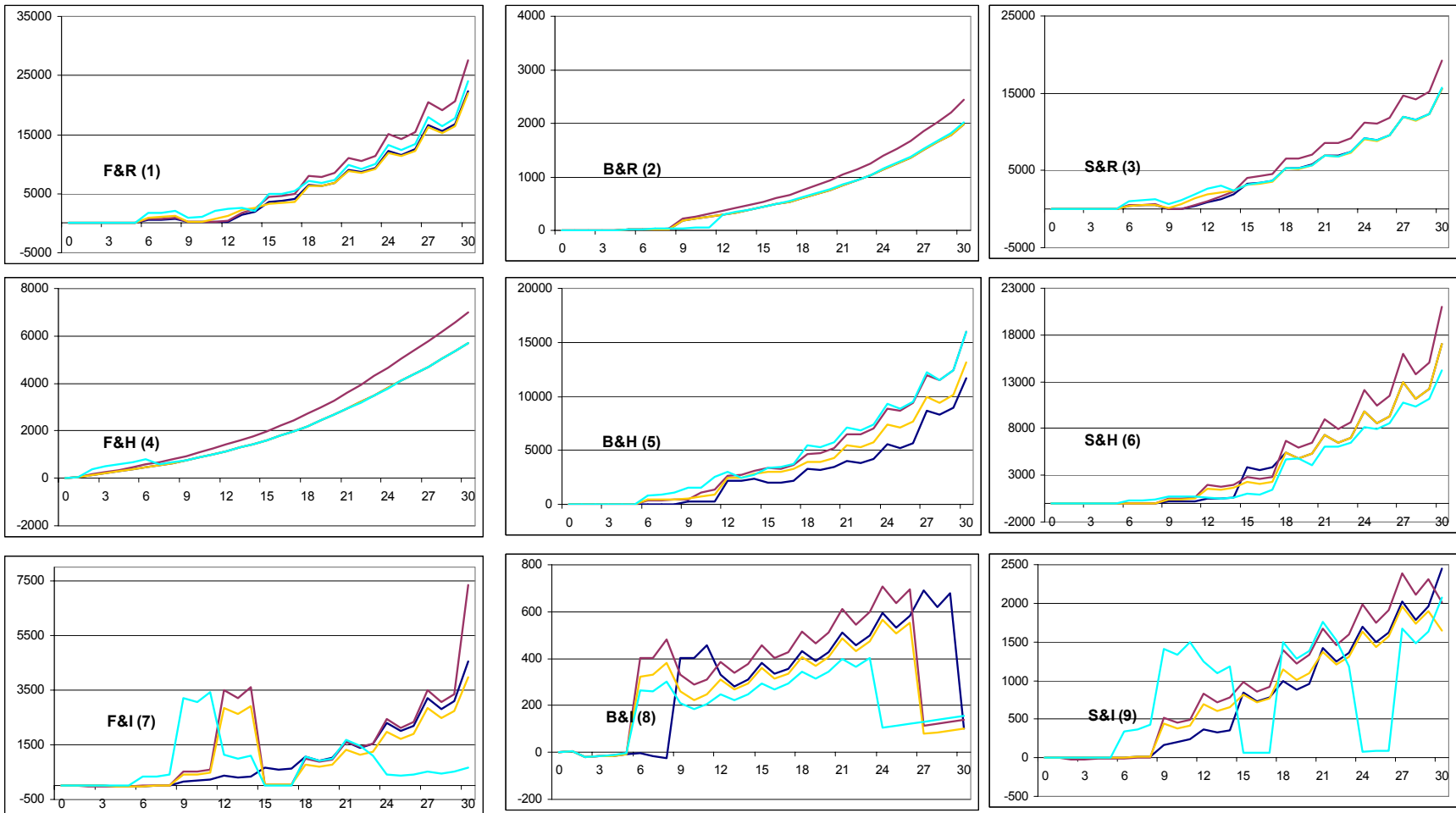


Figure 7- 47 Comparison of the effects of different government interventions on the economic performance (in mZAR) of bioenergy network over 30 years (legend on next page)

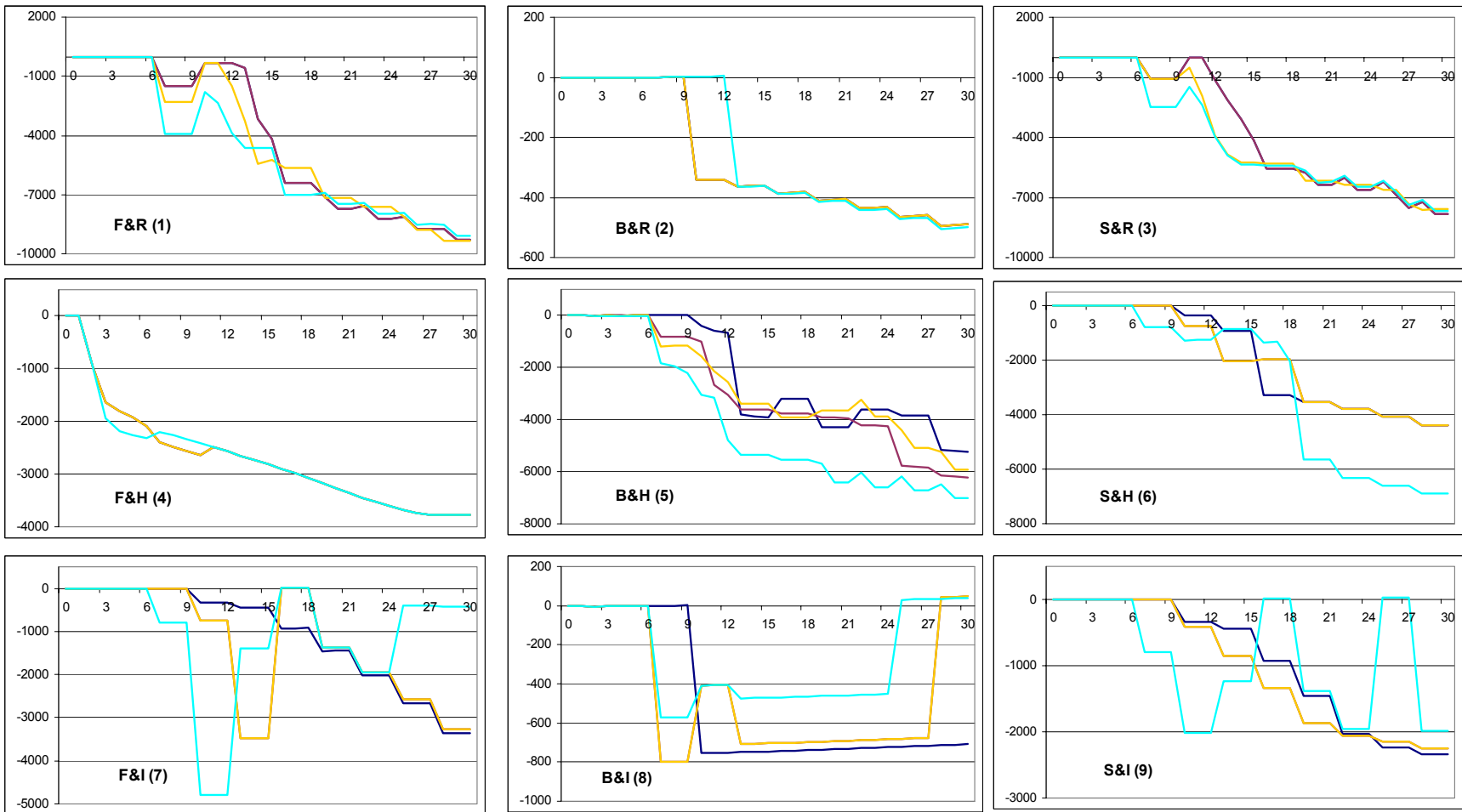


Figure 7- 48 Comparison of the effects of different government interventions on the environmental performance (in kTonnes CO2 emission) of bioenergy network over 30 years (legend on next page)

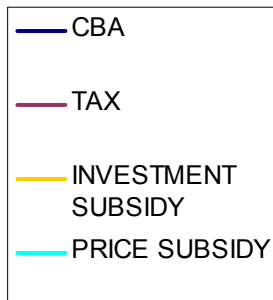


Figure 7-45 shows that different policy instruments have different effects on the financial position of the government. Price subsidies can have marginal better returns for government, but can also have negative effects on the network evolution. For example, in scenario 5 price subsidies have a positive effect on the network evolution, while in scenario 8 they have a negative effect. Investment subsidies require

largest expenditure in the beginning of the network evolution, however can under some circumstances lead to network evolutions that perform better than without government interventions (5, 7 & 8). A better performance of the bioenergy network in terms of total energy production equates to more tax revenues. Policy intervention through tax reductions have in general no positive effect on network evolution and reduces overall benefits for SA government.

Figure 7-46 show that policy interventions in terms of price subsidies, investment subsidies and tax reductions have only minimal effects on the social performance of network evolutions, especially in comparison to the introduction of MAUT or ELECTRE III as strategic decision making tools. It can therefore be concluded that decisions involving infrastructure development cannot be stimulated by the economic incentives explored, but merely benefit from explicit consideration of the social and environmental benefits of infrastructure development.

In terms of overall profits generated throughout the network evolution, figure 7-47 shows that tax reductions are beneficial for the economic performance of network. Except for scenario 5, any other policy intervention has no or negative effects on the economic development of a network evolution. Although this is a counter intuitive outcome, it is an important observation that economic policy incentives do not benefit the economic performance of a network. Instead, policy interventions change the evolution of a network and this can have subsequently effects on the economic performance. Thus, policy interventions should always be developed with their impact on the network evolution in mind rather than perceiving these interventions as 'economic boosts' for the system.

Finally, figure 7-48 shows that policy instruments can provide both positive and negative effects on the environmental performance of the network evolution. These effects can be both very positive and negative, depending on the mental models that organisations employ. Especially price subsidies can alter the development of the network evolution and has sometimes very positive (scenario 5 & 6) and sometimes very negative (scenario 8 & 9) effects on the environmental performance of the network evolution. Similar to the observations on the economic performance, it can be concluded that policy interventions should be developed on the basis of their effects on the network evolution rather than viewing them as arbitrary stimuli for the development of a bioenergy network.

7.7 Comparison of different interventions

Section 7.3, 7.4, 7.5 and 7.6 have used agent-based scenario analysis to explore the effects of interventions on sustainable development of network evolution. These sections have only focused on the consequences of interventions on economic, social and environmental performance of different evolutionary pathways. However, in chapter 4 it was argued that it is important to consider structural features of sustainable development as well as their potential contribution to the socio-economic and bio-physical environment in which they operate. Furthermore, section 5.5 in chapter 5 argued that the evaluation and development of interventions in uncertain circumstances requires a methodology to explore the robustness of interventions over a range of possible scenarios.

Section 5.5 discussed how scenario-based goal programming (SBGP) can be used to evaluate the robustness of policy instruments. It argued that by comparing the performance of an intervention towards aspiration levels over a range of scenarios, it is possible to determine which intervention scores best in terms of average performance (an Archimedean norm whereby both α and β in equation 5-2 equal 1) or in terms of a robust performance over all scenarios and criteria (a Tchebycheff norm of α and β in equation 5-2 equal to ∞). This section compares the different interventions to each other with regard to both the structural and functional criteria for sustainable development suggested in chapter 4 and applied in section 7.3 over the whole range of different agent-based scenarios (the nine different mental models). The final evaluation of the 'best' intervention depends on the weightings for each criteria, the weightings for each

scenario and the values of α and β . These values depend on the analyst's view and need to be elicited through stakeholder participation.

The next table shows a quantitative evaluation of different interventions on network evolution. The quantitative scores in table 7-24 are constructed by taking the best performance for any indicator in any year as aspiration level. The use of year-specific aspiration levels reflects the view that there are inherent constraints to the performance of the industrial network within each year, because of the external environment in which it operates (availability of bagasse, price of electricity, oil prices etc). An evaluation on the basis of year-to-year performance takes these external constraints into consideration.

In practice, this means that for the first set of results each criteria in each year has a different aspiration level. Subsequently, the score for an intervention is calculated by the difference between the actual performance of the intervention in a particular criteria for a particular year in a particular scenario and the aspiration level. The values displayed in table 7-6 are the total sum of deviations from the aspiration levels for any interventions. The intervention that has the minimum difference between the aspiration level and the actual performance over all the nine different scenarios can be viewed as most robust.

Table 7- 6 Quantitative comparison of effects of different interventions on sustainable development of the bioenergy network

	standard	maut	electre III	price subsidy	investment subsidy	tax reduction
economic efficiency	202	179	166	198	196	199
environmental efficiency	159	167	139	156	151	156
social efficiency	182	118	109	180	175	182
economic effectiveness	144	130	157	150	148	147
environmental effectiveness	147	132	110	150	151	144
social effectiveness	182	121	110	188	189	183
economic resilience	177	176	185	283	140	245
environmental resilience	141	144	160	142	132	139
social resilience	91	113	125	101	100	91
economic adaptiveness	145	153	119	136	138	136
environmental adaptiveness	203	137	126	196	183	195
social adaptiveness	133	96	68	132	124	128
economic contribution	206	151	120	197	184	184
environmental contribution	188	136	96	180	167	183
social contribution	77	32	30	77	77	76

The table shows that ELECTRE III is preferred in terms of stimulating economic, environmental and social contributions of the bioenergy network. For structural features, the preference for interventions changes between 'no intervention', MAUT, ELECTRE III and investment subsidies.

The table should be used with caution. The full impact of sustainable development is a complex issue and a single number does not reflect the true complexity of any of the processes that play a role in industrial network evolution. Furthermore, the results shown in table 7-6 are only valid for the context in which this analysis has taken place, which

means that these numbers can change dramatically if the context in which the bioenergy network evolves is not similar to the 'business-as-usual' scenario. Finally, it is important to understand that the actual evaluation of interventions depends largely on the requirements from the analyst in terms of what criteria are important and whether an average performance is preferred over a robust performance. Thus, a preferred performance in a large number of criteria does not necessarily mean that that particular intervention is preferred from an analyst perspective.

Despite these reservations, the methodology shows that it is possible to analyse and evaluate the consequences of interventions on industrial network evolution. The methodology provides clear insights in the complex processes that govern network evolution and they provide a framework in which to evaluate the different sustainable development criteria. Finally, from a pragmatic point of view it does provide decision makers⁶¹ with a more coherent understanding of the potential consequences of their actions and allows them to develop and introduce interventions that are most aligned with their intentions.

7.8 Conclusions

This chapter has used the methodology developed in this thesis to analyse a bioenergy network in the region of KwaZulu-Natal in South Africa. The first two sections have discussed how strategic decision making processes of different existing and potential organisations within the network can be operationalised. A set of nine different mental models is suggested, which can be used as a basis for nine different agent scenarios exploring how organisations' perceptions about future uncertainty result in different evolutionary pathways. The use of this model is illustrated within a 'business-as-usual' context scenario, which represents the analyst perspective of the context in which the bioenergy network might evolve. This chapter has demonstrated the value of this methodology for analysing and exploring the complex processes associated with industrial network evolutions. The results show that within this 'business-as-usual' scenario, there are many different evolutionary pathways possible depending how organisations perceive their environment and make strategic decisions about technology investments and contract partners. The different pathways display an green energy production ranging between 5 PJ p.a. to 40 PJ p.a., the number of generators operating

⁶¹ It is important to note that the 'analyst' or the 'decision makers' can be a group of stakeholders.

in the network can range between 2 and 14 and it is possible to reduce CO₂ emissions up to 10 million tonnes p.a. (although under some scenarios CO₂ emissions might increase). The implementation of infrastructure technologies also shows a large variety depending on the interaction between concessionaires and local governments and decentralised power production of local sugar mills. The chapter has shown that by systematically exploring the functional and structural characteristics of each pathway, it is possible to deduce particular network features that promote sustainable development of the system. The final two sections of this chapter have explored two categories of potential interventions to stimulate sustainable development of the network; policy instruments and the introduction of decision tools that explicitly consider the social and environmental consequences of investment decisions. The results have shown that each intervention can have both positive and negative consequences depending on the mental models that organisations use within the network. The true value of this analysis is, however, that it provides decision makers with a clear understanding of how interventions impact on the process of industrial network evolution rather than on a particular end state of the system. Such understanding provides the starting point for creating better interventions that explicitly promote those processes that drive sustainable development.

Discussion, conclusions and recommendations

8.1 Introduction

The final chapter of this thesis is divided into three sections. The first section discusses the analytical framework, methodology and modelling tools developed in this thesis in the context of the research questions and its application to the case studies. The discussion will place the contributions of this thesis in the context of other academic work focusing on stimulating sustainable development, and also highlights potential applications and limitations of this thesis in terms of the analysis of other complex adaptive systems. The second section will present the main conclusion of this thesis and the contributions made throughout this work. The final section will provide some recommendations for future work.

8.2 Discussion

The central research question in this thesis has been the following:

How does organisational behaviour affect industrial network evolution; and which interventions can stimulate sustainable development of industrial networks?

This section will discuss the methodologies that have been developed to address this question in five sections, following the outline of chapter 1, which posed the following specific questions:

1. What are the major determinants of organisational behaviour in industrial networks?
2. How does organisational behaviour affect the performance and evolution of industrial networks?
3. How can sustainable development of industrial networks be evaluated?
4. How can the effect of interventions in industrial networks, designed to stimulate sustainable development, be analysed and evaluated?
5. Which methods and tools are available to analyse the previous three questions?

Furthermore, this section will provide a discussion on the bioenergy case study and how the results might be used to stimulate sustainable development in KwaZulu-Natal.

8.2.1 Organisational behaviour

In most economic studies of industrial networks, it is assumed that organisations behave rationally, trying to maximise their economic utility. Despite there being neither logical nor empirical evidence that organisations actually behave in this manner, this assumption of rationality prevails in many studies that explore the impacts of (policy) interventions on industrial networks (Conlisk 1996; 2000:4; NEF 2005) .

Chapter 2 has provided a detailed overview and discussion of a large set of alternative models that have been developed to explain organisational behaviour in industrial networks. This chapter concludes that organisational behaviour is informed by four different network characteristics:

- Functional characteristics
- Implicit behavioural characteristics
- Implicit relational characteristics
- Implicit network characteristics.

Functional characteristics are defined as those characteristics that are formally recognised by the organisations operating within a particular network. Examples of functional characteristics are the price of product, the location of a production facility or infrastructure available. Implicit characteristics are defined as those characteristics that impact on the decision making process, but are not formally recognised within the network. On a behavioural level, implicit characteristics consist of particular attitudes towards risk, preferences or individual values manifested by organisations which make

up the network. Implicit relational characteristics consist of, most notably, trust and loyalty. These affect how organisations choose between different potential relationships, which, in turn govern the flow of resources within the network. Finally, there are implicit network characteristics, such as social norms and values, which arise through social embeddedness. These too impact on the decision making processes within the network. Together, these four types of characteristics and the information flows which link them form the basis of a four-level analytical framework for industrial networks.

Most studies in social psychology, administrative sciences and economics focus on only one, or a limited number of these four level and try to elicit specific processes that explain how particular variables affect the decision making process. Whilst these historical and empirical studies do make a contribution, a full understanding of organisational behaviour (and decision making) and its impact on network performance can only be gained through analysing the interactions between the different levels of the analytical framework proposed in this thesis. The analytical framework represented in figure 2-2 allows for explicit consideration of all four levels of industrial network characteristics and how they impact on organisational behaviour. The advantage of this framework is that it provides a structured approach for analysing the relationship between organisational behaviour and industrial networks as well as for identifying which processes (and industrial network characteristics) need to be considered in order to develop comprehensive models of industrial network evolutions.

8.2.2 Industrial network evolution

Industrial network evolution is the result of interactions between multiple organisations acting and responding to each other in a common environment. However, no linear relationships exist between actions taken on an organisational level and industrial network performance on a systems level. Instead, industrial network performance can be best described as an emergent property on a systems scale (Shrivastava 1995; Newton 2002) and can only be analysed by focusing on the interaction between subsystems causing these emergent properties to unfold. Several researchers have recognised that a complex adaptive systems' perspective developed by Holland (1995) is required to analyse complexity in industrial networks (Weisbuch 2000; Choi, Dooley et al. 2001; Tesfatsion 2002). An analysis of industrial network evolution from this perspective requires explicit consideration of the attempt by organisations to pursue their individual

objectives within the context of a constantly changing environment. The interactive process between organisational action and industrial network characteristics is driven by the strategic decision making process of each organisation: a 'set of consistent behaviours' that organisations employ to match their internal capabilities to their external environment (Ansoff 1965; Mintzberg 1978; Porter 1980; Eisenhardt and Zbaracki 1992).

Chapter 3 has analysed different models of strategic decision making processes and has placed a simplified model within the context of the analytical framework discussed previously (see figure 3.6. in chapter 3). Together, these form the basis for the development of simulation models to analyse industrial network evolutions. However, there are many different ways and descriptions of how organisations make strategic decisions. Equally, chapter 2 has shown that there are many different ways in which organisations are affected by the different industrial network characteristics. Thus, although the modelling platform developed in chapter 3 forms the basis for analysing organisational behaviour within the context of industrial networks, it does not explain why industrial network evolutions evolve in a particular way.

The question of what determines industrial network evolutions has been explored in more detail in chapter 5. It is argued that the most important driver for industrial network evolution is an organisation's perception of the uncertainty⁶² inherent to any strategic decision. Uncertainty in industrial networks has two dimensions: 1) organisations are unable to comprehend the full complexity of their environment, either now, or in the future and 2) organisations can never be sure what the consequences of their strategic actions will be. In order to deal with the unquantifiable uncertainty inherent in strategic decisions, organisations employ mental models. The role of mental models in industrial network evolution is to convert a situation of ambiguity or ignorance into a situation that can be made 'sense' of. Mental models make 'sense' through two consecutive processes. Firstly, a mental representation of the external world is created, which provides information to a decision maker. Secondly, mental models provide a set of cognitive processes that represent the decision makers' interpretation of this information and how it is converted into a particular action. The form of the mental model depends

⁶² The term uncertainty is used in this thesis to describe an unknown future. Other scholars use ambiguity or ignorance to describe the state of an organisation faced with an unknown future. However, the term uncertainty is used here to reflect that organisations attempt to deduce ambiguity or ignorance to uncertainty by employing mental models.

on the organisations perception towards future uncertainty, an inherent characteristic of industrial networks. In essence, the mental models form the link between the complexity of the industrial network evolution and the organisational decision making creating this complexity. This thesis has argued that by systematically exploring different mental models in an agent-based modelling platform, it is possible to explore the potential evolutionary pathways of industrial networks.

This thesis argues that in order to understand industrial network evolution one has to understand how different mental models result in different network evolutions. The analytical framework developed in chapter 2 and the model of strategic decision making developed by Mintzberg, Raisinghani et al. (1976) and translated into an agent-based model in chapter 3 allow for exploring the two components of mental models and how they impact the network evolution. The analytical framework is sufficiently generic that it can capture different mental representations employed by organisations in their mental models to deal with uncertainty about the environment. On the one end of the spectrum, organisations can ignore uncertainty and focus on the functional characteristics apparent in the network. On the other extreme, organisations can employ social norms and values to interpret the world and inform their decision making process. In a similar vein, Mintzberg's model of strategic decision making can represent different cognitive processes that can be employed by organisations in mental models to deal with uncertainty about the consequences of their decisions. On the one end of the spectrum, organisations can attempt to quantify consequences of their actions and act accordingly. On the other end, organisations can imitate other organisations instead of attempting to evaluate the consequences of their actions. Chapter 5 has proposed nine different mental models to explore different industrial network evolutions (see figure 5-6 in chapter 5).

Other academics, most notably in the research fields of agent-based modelling and system dynamics, have placed emphasis on the role of 'mental models' for analysing complex systems. However, system dynamics has mostly focused on the 'mental model' of the analyst rather than the 'mental models' of the organisations that exist within an industrial network (see Forrester 1961; Doyle and Ford 1998; Sterman 2000). Agent-based modelling considers explicitly the bounded rationality, or mental models, of agents in complex systems (Reusser, Hare et al. 2004:3; Janssen 2005:6). However, the unique

contribution of this thesis is a methodology to systematically analyse the effects of mental models and their relationship to industrial network evolutions. Included in these mental models are consideration of the way in which organisations define their environment and the cognitive processes that inform their decision making. These mental models are integrated into scenarios which, together with various “world views” to accommodate future uncertainties, provide the basis by which the evolution of industrial networks can be explored. Secondly, this thesis has made a substantial contribution to the analysis of future uncertainty by combining an analysis of industrial networks to an approach to aid strategic planning. The agent-based model has been used to explicitly explore the role of organisational behaviour in the evolution of industrial networks, while the combination of scenario analysis and goal programming allows decision makers to evaluate and develop interventions that stimulate industrial network evolutions towards sustainable development. The advantage of this combined approach is that agent-based scenario analysis systematically explores the role of uncertainty in industrial networks from the perspective of the organisations within the network, as well as from the perspective of any analyst interested in the network. As such, the combination of the two approaches provides a methodology that explores 1) *why* industrial networks evolve in a particular direction and 2) *how* industrial networks can be stimulated towards sustainable development.

Despite the advantages of agent-based scenario analysis over more traditional approaches of scenario analysis, there are still some limitations in terms of how comprehensive this approach is in exploring future uncertainty. In this thesis the methodology is illustrated using nine discrete scenarios of ‘mental models’, whereby it is assumed that within each scenario all organisations use the same mental models. In reality, however, organisations use a range of mental models depending on their decision situation and/or they use mental models unexplored within this thesis. Furthermore, they might change their mental models throughout the course of history and within each mental model it is possible to explore different parameters for thresholds or relationships. The use and exploration of different mental models deserves further research and might be able to advance our understanding of how networks evolve. However, it can be argued that the methodology developed within this thesis provides a solid basis from which to start such explorations rather than to randomly explore all

possible parameters and processes that might impact on the future of industrial networks.

8.2.3 Sustainable development of industrial networks

There are a large number of sustainability frameworks that provide different methods and indicators to evaluate sustainable development of systems. However, only a relatively small number of these are capable of dynamic analysis of different evolutionary pathways of a particular system. Most frameworks apply only to analysis of discrete system states. Few frameworks focus on both the function of the network and its underlying dynamic (and structural) features simultaneously (Sartorius 2006; Hooker 2007; Voinov and Farley 2007 are exceptions). The dynamic features of evolutionary pathways pose several challenges for the evaluation of sustainable development, which have been addressed in this thesis by evaluating and combining different approaches for evaluating sustainable development.

Chapter 4 defined sustainable development as a process of ‘creating what should be’ rather than ‘fixing what is’ (Ehrenfeld 2007:78). The evaluation of sustainable development pathways of industrial networks poses three challenges. Firstly, industrial networks are open systems and their contribution to sustainable development depends on the context in which they operate. As such, the focus of any evaluation has to be on the positive contribution that an industrial network evolution can make to the larger socio-economic, and biophysical environment in which it operates. Secondly, industrial networks can differ in structural features but provide the same functionality (ie contribution to the large system in which they operate); and equally have the same structural features but provide different functionalities. Consequently, a methodology to evaluate the contribution of an industrial network to sustainable development has to take into consideration both function and structure of the network simultaneously. Furthermore, the methodology has to be able to take into account the dynamics of industrial networks. Industrial networks are complex adaptive systems, their function and structure change constantly and at different stages of an evolution their context can change. A methodology to evaluate sustainable development will therefore have to evaluate its contribution at any point in time throughout the network evolution. Although each of these challenges has been addressed in separate frameworks, to the best of my

knowledge, there is no framework that addresses the complex characteristics of industrial networks simultaneously. This is an explicit aim of this thesis.

The methodology developed in this thesis argues that three features of industrial networks need to be considered holistically to address the challenges discussed in the previous paragraph. Firstly, a systems approach is required to evaluate sustainable development to reflect the importance of the collective contribution of organisations within an industrial network, rather than their individual performances. Such an approach also explicitly considers an industrial network as a nested system, within a larger socio-economic and biophysical system (Jackson 1996). From this perspective, any contribution of an industrial network should, as such, be evaluated on the basis of a life-cycle approach, which takes into consideration the impacts of all organisations involved in an industrial network.

The methodology explicitly recognises that defining positive contributions is a normative process, which depends on the stakeholders involved, their moral and ethical perspectives, the time of the evaluation and circumstances under which the evaluation is executed. Therefore, use of the (functional) contribution of an industrial network as an evaluation criterion is a necessary but insufficient criterion for evaluating the network's contribution to sustainable development. In this light, four different structural features have been suggested as evaluation criteria: efficiency, effectiveness, resilience and adaptiveness. Efficiency and effectiveness relate to the operational features by which an industrial network provides a particular contribution to society and addresses the need to evaluate both function and structure simultaneously. Efficiency is the ratio of quantities entering and leaving the system, while effectiveness reflects the ratio of the quality of resources entering and exiting the industrial network. The importance of differentiating between efficiency and effectiveness has become clear in the case study analysed in this thesis. A bioenergy network based on bagasse as a resource might be less efficient than a network based on food crops, but it is more effective in that it uses a lower quality input to produce the same quality of output. By coupling efficiency and effectiveness to an evaluation of a particular contribution, the method is able to differentiate between different network evolutions where the contributions are similar, but the structural features are different.

Resilience and adaptiveness relate to the dynamic features of an industrial network, and whether the system is able to accommodate future stresses to the system. Again, the difference between resilience and adaptiveness is important, especially in the context of industrial networks⁶³. This thesis has argued that resilience for socio-economic systems can be defined as the system's capacity to maintain a particular contribution if faced with temporary shocks. Adaptiveness, on the other hand, is defined as the system's capacity to change its contribution if faced with permanent changes. By coupling resilience and adaptiveness to evaluation of a particular contribution, the method is able to differentiate between systems that are more or less vulnerable to temporary shocks or permanent shifts.

The final challenge in evaluating industry networks in the context of sustainable development is to accommodate possibly conflicting objectives associated with both their functional and structural features. To this end, chapter 4 has adopted and developed a set of indicators to consider structural features of industrial networks with respect to the contribution of the system to sustainable development. Furthermore, this chapter discussed and suggested several multi-criteria decision analysis tools, which can find application depending on the analyst's view on "weak" versus "strong" sustainability. These can be employed to provide information relating to stakeholder preferences and value positions towards particular normative or structural features of the system (Munda 2005; Polatidis, Haralambopoulos et al. 2006).

The aim of this method has been to provide a more rigorous analysis of how evolutionary pathways might be evaluated in accordance to sustainable development. However, there are still limitations to this approach that require further work. First of all, it should be mentioned that the additional benefits of this dynamic approach come with additional data requirements for value functions, weightings and additional data handling procedures. For simple industrial networks, which do not display different structural dynamics, this approach would be too cumbersome. A second important limitation of this approach is that it provides a comparison of evolutionary pathways on the basis of

⁶³ The term resilience has been developed in ecological studies of ecosystems. In ecosystems, resilience refers to the ability of a system to maintain itself, whereby the specific function of the ecosystem is not of importance. The function of industrial networks, on the other hand, is not survival, but is intrinsically related to the particular contribution they provide to the larger socio-economic system in which it operates. This has important ramifications for the understanding of resilience, because maintaining functionality and maintaining the system do not have the same meaning for socio-economic systems.

'snapshots' without any consideration if this performance takes place at the beginning or at the end of an evolutionary pathway. Instead, one could consider how functional and structural criteria develop over time, preferring those systems that increasingly improve their functional and structural feature over time⁶⁴. Thirdly, the role of discounting in the evaluation of sustainable development considers more attention. It can be argued that industrial networks themselves do not have any value, but that they are instruments for goods and services. If in the future there might be other instruments by which goods and services can be provided, then it can be argued that the future value of industrial networks is of less importance than their current contributions. However, transitions of industrial networks require long time frames and investments today should be balanced by long term benefits. A methodology that would be able to value both aspects of industrial networks is, to my knowledge, not available yet. A third point of discussion is the set of structural indicators that has been developed within this thesis. It can be argued that the choice of these structural indicators is a normative choice in itself, reflecting the modeller's perspective on what structural features are important for an industrial network. From this perspective, more research is required to address the question how far different functions (or different industrial networks) require different structural features to be assessed.

8.2.4 Interventions

The problem of sustainable development is not a lack of vision. Most people would agree that industrial networks that produce goods and services increasing quality of life in an efficient, effective, resilient and adaptive way are a good reflection of sustainable industrial networks. However, the problem of sustainable development is that the transition from the current system state into a desired state is a complex process driven by a large number of interacting autonomous decision makers, each with limited control over the overall direction of the network evolution. Even if all decision makers aim for the same end result, the complexity of industrial networks essentially guarantees that the end result will be different to the sum of individual actions intended to achieve that end result.

⁶⁴ For example, this could be achieved by using the derivative of functional and structural performance criteria as the basis for evaluating the sustainable development of industrial network evolutions.

This underlying complexity makes it impossible for organisations to understand which interventions will stimulate sustainable development of industrial networks. The methodology and modelling approach developed in this thesis has attempted to address this complex issue by providing a way to explore how interventions might affect sustainable development under different scenarios of industrial network evolutions. The scenario analysis proposed consists of two stages. The first is a traditional scenario analysis approach, whereby the analyst (ie the person or organisation leading strategic interventions) develops a set of scenarios representing his/her mental models of a future world. These scenarios represent different contextual futures for industrial networks under analysis. The second stage is the use of agent-based scenario analysis to explore how organisational behaviour affects the effectiveness of interventions stimulating sustainable development within a particular context scenario. In the agent-based scenario, each agent scenario represents different mental models of the organisations within the industrial network. The different mental models that organisations employ are based on different organisational perspectives towards the inherent uncertainty of the future and together provide a means to explore different evolutionary pathways that can occur within a particular future.

The results of this approach form a set of quantitative values expressing the extent to which an intervention has stimulated sustainable development under different evolutionary pathways. Since it is impossible to know which pathway represents most accurately the 'true' future of an industrial network, there exists no 'optimal' intervention (Rosenhead, Elton et al. 1972:414). Instead, a 'scenario-based goal programming' (SBGP) method developed by Durbach and Stewart (2003) is adopted to evaluate how robust interventions are in terms of their performance under any of the scenarios (Durbach and Stewart 2003; Lempert, Groves et al. 2006).

The methodology has been applied to a bioenergy network in the province of KwaZulu-Natal in South Africa, which results are discussed in more detail in section 8.2.6. This thesis has examined two categories of interventions. The first consists of different forms of financial subsidies that can be introduced by national governments to stimulate the development of the industrial network in a particular direction. The second consists of changes to strategic decision making processes that organisations employ in the network. The application of this exercise to the bioenergy case study has illustrated the

use of this method in exploring the advantages and disadvantages of different interventions and their value in stimulating sustainable development.

An important point of discussion is the degree to which one should pursue quantitative answers for evaluating interventions in complex systems like industrial networks. The use of SBGP requires a large amount of input from stakeholders, which are involved in difficult cognitive processes to elicit the explicit value functions and weights associated with the performance criteria and scenarios. Several (experimental) studies on the use of value functions and weights have shown that little variations in the methodology, or biases in the heuristics employed by the decision makers can result in completely different weightings and therefore different quantitative answers (Pöyhönen and Hämäläinen 2000; Pöyhönen and Hämäläinen 2001). From this perspective, the true value of an explicit quantitative comparison of the interventions can be questioned. On the other hand, it can also be argued that decision makers, especially when faced with complex decisions, require (and often demand) quantitative values to base their decisions upon. In those cases, a quantitative evaluation derived from a process that explicitly recognises and engages with the complexity of industrial network evolutions is more appropriate than a more simple approach that has no connection to reality.

8.2.5 Model development

The basis for the model development in this thesis included two modelling requirements: 1) models need to be able to provide information about the causal relationships between interventions and industrial network evolutions and 2) models have to represent the complexity of industrial networks accurately.

Chapter 3 has discussed several modelling approaches and tools and their applicability to complex adaptive systems. In general, there is consensus that models of complex adaptive systems are not predictive, but that their purpose is to create an understanding of the underlying processes that drive the evolution of complex systems. Under these circumstances, simulation is the most appropriate modelling approach (Simon and Newell 1958:6; Nance and Sargent 2002; Axelrod and Tesfatsion 2005:4). In other words, models of complex adaptive systems should be seen as 'opaque thought experiments' (Di Paolo and Noble 2000) that allow the analyst to explore how the future unfolds under particular assumptions (Kay, Regier et al. 1999). In addition, this thesis

argues that simulations can also be used to develop robust interventions using scenario analysis.

To represent the complexity of industrial network evolutions within a computational model, this thesis has adopted an agent-based modelling (ABM) approach. ABM are used to explore the complex interaction between organisational behaviour on one level and the system performance on another level (Axtell, Andrews et al. 2002; Bonabeau 2002; Lempert 2002). Furthermore, ABM is a flexible tool that can easily be associated with other quantitative and qualitative methods for policy making related to sustainable development (Boulanger and Brechet 2005).

The ABM developed in this thesis consists of four scales:

1. the strategic decision making process of individual organisations within the network,
2. their mental models and how they perceive and respond to the world ,
3. the industrial network as a whole and its performance in terms of function and structure and
4. the processes that govern the social embeddedness of organisations.

The use of four scales is different from many other ABMs. It increases the multi-scale complexity of the model and therefore provides a more accurate representation of the complex processes that determine 'real world' systems. However, it requires that ABM is augmented with system dynamics models to represent the social processes that take place within the environment. Furthermore, the initial parameterisation of the model is informed by average values rather than probability distributions or random numbers. This means that the ABM in this thesis is used deterministically. The reason for this decision is twofold. Firstly, the use of a deterministic model allows exploring the exact consequences of interventions on the network evolution (which is impossible to analyse in models with normal distributions and randomness). The second reason is the purpose of ABM in this thesis. ABM is used as an analysis tool to explore how different organisational behaviours affect the network evolution. From this perspective, the initial

uncertainty in parameters is less of a concern, but the purpose of the model is to explore how the perception about uncertainty affects the network evolution⁶⁵.

8.2.6 Case study results

The methodology developed in this thesis has been applied to a bioenergy network in the province of KwaZulu-Natal in South Africa. The bioenergy network has the potential to contribute in terms of economic, environmental and social development in the province. However the evolution of the industrial network depends on interaction between existing sugar mills, the current electricity generator and the potential entrance of green electricity, biofuel and biogel producers. Furthermore, the evolution of the industrial network is affected by international corporations and local governments involved in large scale electrification of the region. Finally, there are at least four different national departments interested in the development of the region, each department with different and conflicting interests. The features of this case study make it an interesting vehicle through which to demonstrate the efficacy of the methodology developed in this thesis. It is similar to many other industrial networks throughout the world, all of which are faced with distributed control of resources, conflicting interests and an insecure future.

The case study results have provided the following insights for stimulating sustainable development of bioenergy network in general and the region of Kwazulu-Natal in particular:

1. In any of the agent scenarios of the “business-as-usual” context, organisations engage in one way or another in the production of bioenergy. This suggests that regardless of the ‘mental models’ employed by organisations, the development of a bioenergy network is likely to happen in the (near) future.
2. Oil prices have an important impact on the network evolution. Increasing oil prices makes production of bioethanol more attractive than electricity production. However, increasing oil prices simultaneously reduces the distance over which it is financially viable to transport (especially wet) bagasse. Thus, increasing oil prices benefit the development of a bioenergy network as long as sugar mills have invested in pelletisers.

⁶⁵ This is not to say that exploring the effects of different probability functions and randomness is not of value. However, in this thesis the focus is on the analysis of organisational behaviour rather than on exploring the effects of randomness on network evolutions.

3. The introduction and diffusion of pelletising technologies within the sugar mills have an important impact on the network evolution and enable more sustainable pathways to develop. However, the market barriers to pelletising technologies are that they are only financially attractive if sugar mills know there is secure market for their product. Simultaneously, the entrance of independent power and biofuel producers depends to a large extent on the availability of dried bagasse in the region. Mutual and long-term contracts between sugar mills and independent producers could overcome this barrier, although from a long-term perspective sugar mills and independent producers are competing on the same market. It is therefore unlikely that sugar mills would like to lock themselves into long-term contracts reducing their own possibilities to start producing power.
4. The results have provided insights in the important role that the emerging market for bagasse plays in the evolution of the network. Currently, bagasse is seen as a waste product with no value. However, as soon as the bioenergy network is established, bagasse becomes a commodity with a particular value. This has important implications for decision making processes of sugar mills, because usage of bagasse for electricity production means that they lose the opportunity to sell bagasse for an attractive price to independent producers. From the perspective of independent producers, the potential for multiple pathways (electricity, biodiesel, bioethanol, biogas or any combination) increases the competition between potential independent producers entering the network, increases the value of bagasse and makes entering the network less attractive. The effects of this emerging market for bagasse are important in the overall evolution of the system and any intervention should consider how it would effect the development of a market for bagasse.
5. The results have shown that there is strong competition between the different alternative uses of bagasse; and that the margins deciding which technologies are installed, and which independent producers enter the network depend on a small number of differences within the contextual situation of the bioenergy network (electricity prices, oil prices, petrol and diesel tax exemptions etc). It is therefore not possible to determine a particular set of technologies that is preferred. On the other hand, the results also show that not every technology or every combination of technologies will result in sustainable development. Thus,

- although there is ‘no silver bullet’, there are combinations and sequences of technologies that are more preferred than others.
6. The total number of household connections that are connected over the time period of 30 years is similar for the range of scenarios investigated. However different evolutionary pathways can be followed to electrify households. There are evolutionary pathways where concessionaires and local governments operate in different municipalities and where these municipalities are gradually electrified. Other evolutionary pathways unfold where both concessionaires and local governments operate in similar municipalities, and where an electrification project from one organisation can affect opportunities for another organisation. In these circumstances, electrification can occur very rapidly within a particular municipality, but the total number of municipalities electrified is less. The reason for these different evolutionary pathways is that the decision making processes of both concessionaires and local governments are strongly affected by density and number of households in a region. When municipalities exceed a certain threshold in these two variables, they become more attractive to electrification either via grid connections or via minigrids. This interdependency should be considered for the development of infrastructure plans.

The following conclusions can be drawn from the analysis of interventions to stimulate sustainable development. Firstly, the consequences of interventions are heavily impacted by the ‘mental models’ employed by organisations. This is particularly true for policy interventions. The same intervention can have complete adverse effects on sustainable development depending on the organisations perception of uncertainty. The reason for this is twofold. Firstly, most policy instruments are related to ‘functional’ targets, measured in terms of a system output indicator, and policy instruments are in place until the system output is achieved. As such, these policy instruments promote pathways that achieve a particular target the quickest way without any consideration of the structural features of the system. Secondly, policy interventions often disadvantage the introduction of radical innovations. This conclusion is substantiated by the following observations. In industrial networks, organisations which pursue incremental innovations are perceived as less risky and are placed in a stronger financial position than organisations that attempt to introduce radical innovations. Financial instruments, like investment subsidies and price subsidies, benefit financially strong organisations

proportionally more than organisations in a financially weaker position. An organisation that is close to investing in an incremental innovation will be able to invest in technology when it receives a subsidy. However, an organisation that attempts to introduce radical innovation will require proportionally more money to invest, and will often, despite the subsidy, not be able to invest. As a consequence organisations with incremental innovations will benefit from subsidies, while organisations that pursue radical innovations will not. From a dynamic perspective, the situation is even more disadvantageous to those wishing to follow pathways of radical innovation, which often requires longer lead times to achieve market penetration. So when radical innovators are finally ready to enter the market, subsidies may already have been abandoned.

In terms of interventions that attempt to change the way organisations make decisions, the following conclusions can be drawn. In those situations where there is little interdependency between organisational actions, organisations that adopt a 'strong sustainability' position supported by MAUT or ELECTRE III will benefit sustainable development of industrial networks. In those circumstances, an increased local performance in sustainable development leads to increased sustainable development on a systems level. In the case study, this is demonstrated by the positive contribution that local sustainable development has on the overall sustainable development of the infrastructure system. However, in those cases where organisation's performance depends on decisions of other organisations within the network, improved local sustainable development does not necessarily benefit the overall performance of a network. For example, the decision for sugar mills to produce electricity on the basis of wet bagasse diminishes the development of the bioenergy network in the long run⁶⁶. A second important finding is that the use of either MAUT or ELECTRE III does not compromise the overall economic performance of industrial network evolutions.

The overall conclusion of the bioenergy network case study is that there is not a single set of technologies or structures that is more preferred for the development of sustainable bioenergy networks. Instead, this thesis has concluded that there are several 'evolutions' of the system that are more preferred than others. The most preferred evolution in terms of sustainable development is one in which an independent

⁶⁶ From this perspective, the current incentives for bagasse-fired combustion in local sugar mills can have an important limiting effect on the future development of the bioenergy network.

power producer enters the market and stimulates the introduction and development of pelletising technologies. An early entrance of bioethanol producers is less preferred, because production of bioethanol does not benefit from dried bagasse, and therefore creates less incentive for sugar mills to invest in pelletising technologies. Furthermore, an early entrance of bioethanol producers defers the entrance of power producers into the network. However, in the long-run, a bioenergy network is preferred that consists of both decentralised production of electricity and centralised production of biofuels.

For infrastructural development, it is argued that those evolutionary pathways that focus on achieving a particular electrification threshold within a particular municipality are more preferred than those approaches that attempt to provide full electrification for each municipality. If there is too much emphasis on electrification of low density municipalities with low electrification rates (eg less than 40%), there are only a few municipalities that benefit from a large amount of financial resources resulting in relatively few connections. On the other hand, an emphasis on household connections rather than density results in full electrification for high density municipalities, but increases the divide between different municipalities. The most sustainable pathway is to electrify municipalities up to a particular threshold, which makes it more attractive for other organisations to enter the network and provide full electrification.

8.3 Conclusion

This thesis has explored how industrial networks can be analysed and how such analysis can contribute to the development of interventions that stimulate sustainable development. The conclusion of this thesis is that organisational mental models play a crucial role in determining industrial network evolution. It is the organisational behaviour towards the inherent uncertainty associated with strategic decision making that determines their actions and therefore the network evolution as a whole. A systematic analysis of different possible organisational behaviours towards uncertainty provides the possibility to explore different evolutionary pathways and their associated consequences for proposed or suggested interventions.

This dynamic analysis provides important insights in the potential evolutionary pathways of industrial networks and how these dynamic features should be considered explicitly in any evaluation of sustainable development. To this extent, this thesis has argued for and

developed a set of functional and structural indicators that reflect the complex processes and dynamic features that characterize sustainable development in industrial networks. The conclusion is that the true value of sustainable development is in a process of creating synergies and opportunities rather than in a particular choice for a discrete set of technologies or particular infrastructure. In other words, although the choice of technologies is important for the performance of a network at any particular point in time, it is the consequences of these choices for the future development of the network that determines the real contribution of interventions for stimulating sustainable development.

Finally, this thesis has demonstrated that an analysis of industrial network evolutions on the basis of an interdisciplinary approach, whereby the insights from socio-psychological and organisational studies are integrated into complex systems tools, developed in biology, operational research and engineering sciences, opens up new avenues for exploring future uncertainty. This thesis has demonstrated that such approach provides decision makers in complex situations with a new method that allows them not only to explore the consequences of their own world views, but also to explore the consequences of responses of those organisations that are actually part of the problem. It is this dual approach, which explicitly engages with both sides of complex problems, that provides the true value of the methodology developed in this thesis.

This thesis has focused on sustainable development of industrial networks, because industrial networks play an important role in shaping our collective future. It is the hope that an increased understanding of the driving forces for industrial network evolution will contribute to better decision making and ultimately a future that provides a better quality of life around the world.

8.3.1 Methodological contributions

Besides answering the central research questions, this thesis has also developed new methodological contributions to the analysis, evaluation and 'design' of complex adaptive systems.

The key methodological contributions of this thesis include:

1. The development of an analytical framework to analyse the position of organisational behaviour within the context of an industrial network. The analytical framework encompasses a set of tools to analyse the complex interaction between organisational behaviour and industrial network evolution, and for relating the role of different theoretical concepts on organisational behaviour within the context of industrial networks.
2. The development of a modelling approach for industrial network evolutions. A non-linear system dynamics multi-scale model is developed that is able to represent the multi-scale complexity of industrial networks, and can be used to create an understanding of the underlying dynamics of industrial network evolutions.
3. This thesis has demonstrated the operationalisation of trust and loyalty as endogenous implicit relational characteristics within an agent-based model. Furthermore, it has recommended the use of the 'Lens model' and 'decision trees' as a means of operationalising mental models within an agent-based model.
4. The development of a holistic approach for evaluating sustainable development of industrial networks. By presenting 'function', 'operational structure' and 'dynamic structure' as three distinct features of sustainable development, this approach addresses the challenges associated with evaluating sustainable development in complex adaptive systems.
5. Recommendations for the development of four structural indicators for analysing the sustainable development of industrial network evolutions.
6. Contributions to the discussion on the role of resilience in the context of socio-economic systems. This thesis has argued that the resilience of industrial networks can only be measured in the context of a particular system functionality. This thesis has introduced 'adaptiveness' as an additional structural feature that describes a systems capacity to provide new functionalities if permanent shifts in a system or its environment occur.
7. The methodological development of agent-based scenario analysis. The methodology consists of agent-based models to explore the role of mental models of organisations within industrial networks on potential evolutionary pathways into the future. These explorations can be used to quantify the robustness of interventions for stimulating sustainable development.

Subsequently, this exploration of potential evolutionary pathways can be grounded in a traditional scenario analysis approach, which explores the consequences of interventions under different future context from an analyst perspective.

8.4 Recommendations

The bioenergy case study that has formed the demonstration basis for this analysis is relatively small and regionally isolated in comparison to many of the other industrial networks that play such an important role in our daily lives. The challenges we are currently facing, including an increasing world population with rapidly diminishing resources, requires that we start addressing organisations in large global industrial networks and their role in not only the evolution of the industrial networks but also the evolution of mankind. This thesis has only started unravelling the complexity of evolution and much more work is required to understand how we might direct our evolution towards a desired state of sustainability. The following recommendations are made for future research:

1. More in-depth analysis is required on indicators for sustainable development; how can efficiency and effectiveness be measured in complex industrial networks with multiple inputs and outputs. Similarly, what are the trade offs between efficiency and effectiveness on the one hand and resilience and adaptiveness on the other hand in other socio-economic systems.
2. More analysis is required on the role of mental models of organisations: both empirical and methodological. Are there particular industrial networks characteristics that make it more likely that organisations adopt particular mental models? What can be said about the distribution of different mental models in organisations in an industrial network? Are particular mental models more or less affective in different industrial networks?
3. More research is required to understand the role of strategic decision making in the context of complex adaptive systems. How does an emphasis on the different stages in the decision making process (ie recognition, development, selection) affect the decision outcome? Are there particular cognitive processes that if adopted collectively will provide beneficial outcomes for all organisations within an industrial network? Does social embeddedness constrain or enable industrial

- networks, especially in the context of sustainable development? Which decision making process result in more efficient and effective systems? Similarly, which processes make industrial networks more resilient and adaptive?
4. More research is required about the role of culture in evolution. How does the globalisation of industrial networks affect culture and how is the evolution of industrial networks affected by combining different cultures into one and the same network? What can be learned from the role of culture in other social structures and how could these lessons be applied to industrial networks?
 5. The application of the methodology should be expanded to other industrial or non-industrial networks. Currently, the framework in this thesis is used to analyse the role of agricultural activities to regional sustainable development and to analyse the effects of personal carbon trading on household energy consumption. However, there are many other industrial and non-industrial networks which analysis could provide more understanding of how we can shape the future towards a more desired end state.
 6. More research is required into the role of innovation. How can the suggested analysis tools be used to plan when and what kinds of innovation are required in the future and when they should be introduced? Is it possible to use the analytical methods suggested in this thesis to provide us with a better understanding of what the requirements will be for future generations? Further research combining the analysis of complex adaptive systems with empirical descriptions of strategic niche management and large-scale transitions could provide a better understanding on how to initiate and shape a transition towards more sustainable pathways.

From the list of recommendations it is clear that there are still many research challenges ahead. Some of these research questions, especially recommendations 1, 4, 5 and 6, can be addressed by advancing the ideas and methodologies developed in this thesis, either by applying the methodology to different case studies or by exploring different processes within the model. However, the more challenging tasks require a more interdisciplinary approach, where social scientists need to work together with engineers to analyse the processes that govern complex systems. This is not an easy task and requires setting aside our disciplinary presumptions and to collect and capitalise on the individual strengths that each discipline brings.

The methodological development within this thesis has provided important insights in how we can start engaging with the inherent ambiguity associated with many of the strategically important decisions that we make. This goes beyond the realm of exploring bioenergy networks or industrial network, but also applies to consumer behaviour in households, international collaboration between national governments or local governance in rural regions. In any of these situations it is not only important to understand the consequences of our own assumptions on the decision outcome, but more importantly to understand the consequences of our assumptions about the behaviour of the others that are involved.

In the context of sustainable development, we are at a crucial stage. Important decisions have to be made about infrastructures for food, mobility and energy, but for most decisions we are still in the dark in terms of what the consequences of our decisions might be. However, we cannot prolong these decisions any longer, because every additional day that we are continuing on our current path has substantial negative implications for future actions. This thesis hopes to contribute to these important challenges by providing a method to explore our current ambiguities more thoroughly. More specifically, it hopes to contribute by opening up the view of decision makers by shifting them away from our current mode of thinking in which we only see our current limitations and constraints towards a mode whereby we can start envisioning different ways of behaviour and the associated opportunities that those might bring us.

This thesis has shown the advantages and scientific contributions that can be made by systematically analysing the complex problem of sustainable development through combining analysis approaches from a complex adaptive systems perspective with the management and design approach used in systems engineering. The hope is that this thesis is a starting point for more research into the question how we can shape industrial network evolutions to contribute to a sustainable future. A future which is so easy to envision for an individual, but at the moment still so hard to achieve collectively.

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A1

Rural electrification in KwaZulu-Natal

A1.1 Introduction

In order to model how rural electrification would affect the evolution of a biomass energy network in KwaZulu-Natal, the current players and regulatory and policy frameworks need to be analysed. With regard to the biomass case-study, three distinct policy frameworks need to be discussed:

- rural electrification via grid
- non-grid electrification
- production of electricity and/or biofuels on the basis of biomass.

A1.2 Electrification in South Africa

The electricity in South Africa is provided by the national utility, Eskom, and around 285 licensed municipalities, represented by the South African Local Government Association (SALGA). Although South Africa has currently one of the lowest prices for electricity in the world, electricity distribution was and has been limited to those areas with economic activities leaving many rural areas unelectrified. 30 percent of the all homes have still no ready access to electricity supply (Davidson and Mwakasonda 2004:14-20). To overcome this backlog, the at that point freshly established National Energy Regulator (NER)⁶⁷ announced in 1994 the largest national electrification programme (NEP) in the world aiming to provide electricity to an additional 2,5 million households before 1999. Eskom, the national electricity generator, was responsible for meeting this target and connected about 1.75 million households and schools and municipalities made close to

⁶⁷ Since march 2005, the NER is converted into NERSA

one million connections (DME 2001). However, the anticipated electricity use of these newly connected households was much lower than anticipated (often less than 100 kWh per month), mainly because electricity is only used for lightning and media and not so much for additional economic activities.

The average costs per connection in this period were R 3213/household and decreasing slowly and the financial IRR for the projects ranged between -5.4% and 21%, with an average of 7.7%. (DME 2001:vi). The monthly operational costs per connection ranged between R19-26 in the period between 1994 and 1999 with average monthly sales around 90 kWh. Eskom's monthly income ranged between the R19-28 (Kotze 2001). The NEP was entirely funded from within the electricity distribution industry by a combination of debt financing and a surcharge on Eskom's tariff. The National Electrification Fund (NEF) is currently governing these funds. However, even the operational costs could often not be recovered by revenue generated. Currently, the minimal rural connection fee is around R2600, which has to be paid up front, and energy charges around 43 c/kWh with a maximum of 4000 W (on the basis of 20A-connection). Specific rural tariffs are also possible, which range between 11-86 c/kWh depending on the season and whether it is peak or off-peak (Davidson and Mwakasonda 2004:21).

However, in 2001 still around 3.3. million households are not connected to the grid. In 2002, the national electrification programme was continued as the Integrated National Electrification Programme (INEP), although the main responsibility for the programme was shifted from Eskom to the Department of Minerals and Energy (DME). The objectives of this programme are to connect an additional 240000 households, 2200 schools and 50 clinics per year. Unfortunately, the INEP has not performed as initially had been outlined in the White Paper on Electrification Policy in 2000. The target of 350000 connected households per year has not been reached and in 2004/2005 only 217000 households were connected. Furthermore, the suggested R3000 subsidy does not seem to cover the costs, which were in 2004/05 on average R4900 per connection (C&V Consulting Engineers 2006:7).

As these electrification programmes were developed and implemented, the White Paper on Energy Policy in South Africa in 1998 also suggested a restructuring of the electricity distribution industry. The 400 individual supply authorities with over 2000 different tariffs

are restructured into 6 Regional Electricity Distributors (REDs), which will need to be in a direct relationship with Local Government who has the constitutional obligation to provide electricity services (DME 2002:1). An overview of the REDs can be seen in figure A1-1.

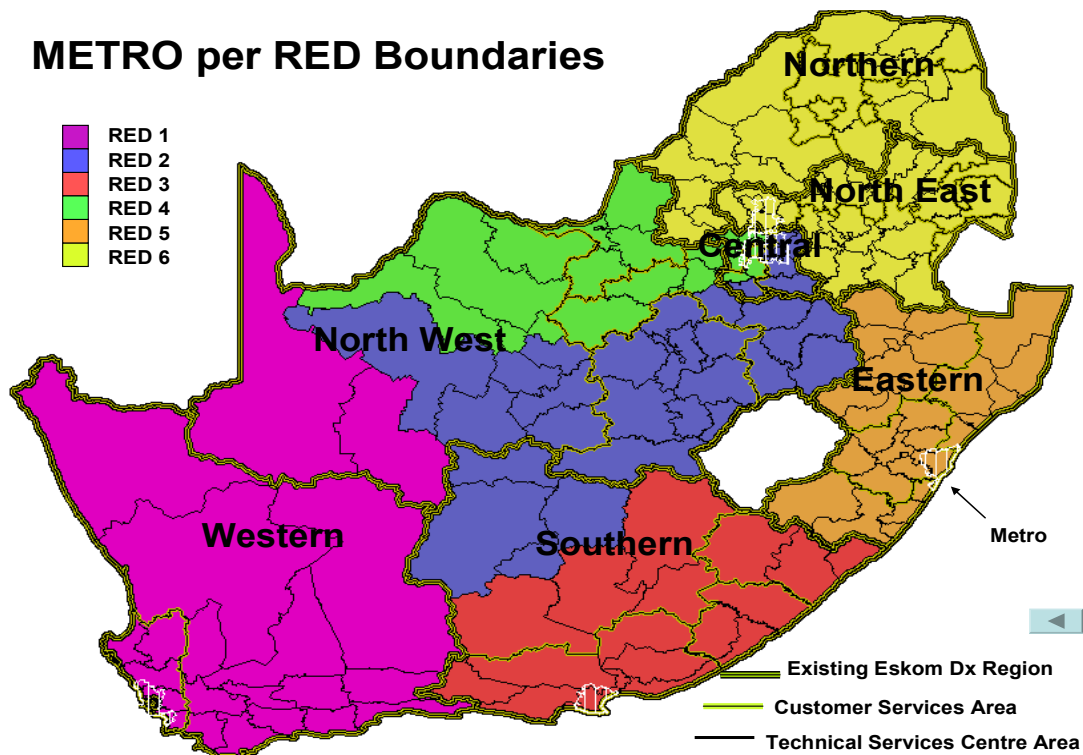


Figure A1- 1 The locations of the 6 proposed Regional Electricity Distributors (REDs) in South Africa (DME 2002)

For those rural areas where grid connections are too expensive, the SA government launched the Non-Grid Electrification Programme (NGEP) in 1999 (Davidson and Mwakasonda 2004:13) as well as a regulatory framework for non-grid electrification (NER 2000). So far the development of non-grid electrification with remote area power supplies (RAPS) had been unsuccessful, because of the high capital costs, poor backup service and maintenance and little user experiences (Ligoff 1991:225) and since then not much has changed. Martens (2001) mentioned the following barriers:

- in principle, grid-extensions have been seen as the most favourable technology
- investments should be evaluated on both current and future cash flows
- the electricity sector industry is undergoing a restructuring process

- the required monthly fee of R50 will not be affordable to a large percentage of rural households (Martens, de Lange et al. 2001:56).

The programme aimed to appoint energy service companies, the so called concessionaires, which would receive the monopoly right to supply energy in return for the installation of decentralised electricity systems. The most advanced concessionaire is the Eskom/Shell joint venture, which established around 6000 solar home systems by 2000. Solar energy seems to be the preferred option because of the low ability to pay of the end-users, the dispersed nature of the households and the lack of institutional end-users. An important role in the non-grid electrification is played by the Independent Development Trust (IDT), which enhances the capacity of government to interact with private and NGO partners and local communities (Martens, de Lange et al. 2001:54). In order to create a level playing field for off-grid technologies, these concessionaires would receive the subsidy as Eskom per established connection, which is R 3000 - 3500. The monthly tariffs that households would require to pay would be around R45 - 58 (Martens, de Lange et al. 2001; Davidson and Mwakasonda 2004).

In order to overcome the inability of households to pay for their electricity bills, the SA government established in 2003 the Electricity Basic Services Support Tariff Policy (EBSST), which provide 50 kWh of grid electricity per month for free and up to R48 of subsidies for those households that have non-grid electrification (DME 2003:6). However, it seems that Eskom only receives up to R 0.45 per kWh, which mounts up to R 22 per month (Scottish Power 2003:30). Funding is provided by the Department of Provincial and Local Government (DPLG) through fiscus grants (DME 2003:18). The subsidies have started showing positive signs with increased use of electricity for lightning and electrical media appliances (Davidson and Mwakasonda 2004:17).

The INEP states that the decision of which technology to utilise for electrification, grid supplies, Solar Home Systems, generators, hybrid systems or any other solution, will be based on life cycle cost analysis and the number of connections made in terms of the budget allocation. However, the DME has announced that it prefers more expensive grid connections over non-grid technology (C&V Consulting Engineers 2006:16). Hybrid-based mini-grid systems will be investigated for remote villages. Furthermore, Eskom has indicated that it does not see non-grid electrification as apart of it core activity,

although it is willing to participate as a concedante on the basis of acceptable agreements with the government. However, there are interesting dynamics in terms of the costs of technologies and the location. Kotze (2001) presents the following findings in terms of capital costs for grid, mini-grid and off-grid technologies:

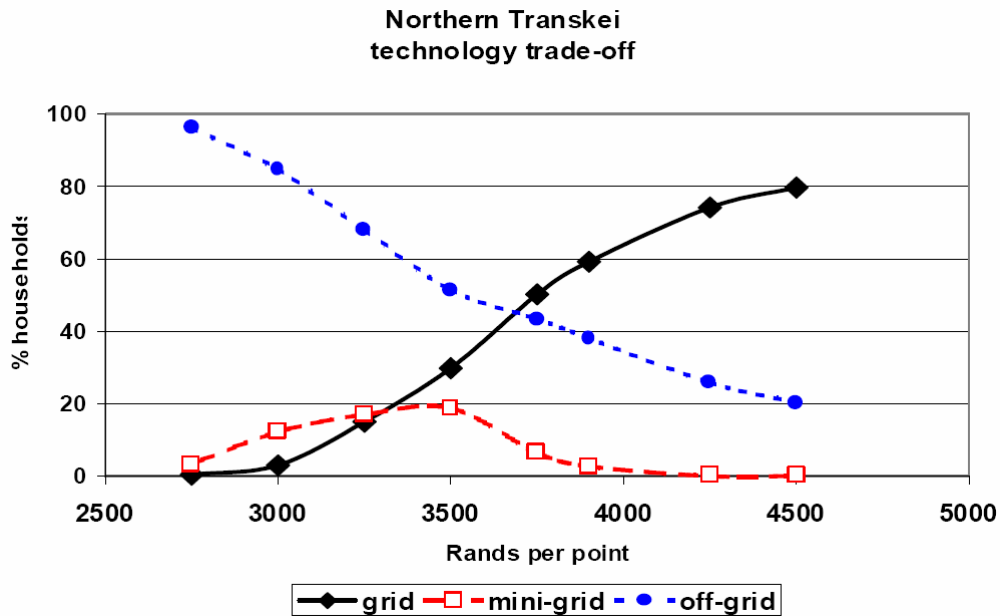


Figure A1- 2 Capital costs in terms of connection points and the technology trade-off in terms of location (Kotze 2001)

Figure A1-2 suggests that the total costs for an electricity distribution network increase with an increase in grid connections. Furthermore, it shows that a combination of off-grid, mini-grid and grid-connections has lower capital costs than a system that consist of more than 50% grid-connections.

In order to overcome the challenge of integrating energy policies into local development programmes, the Integrated Development Planning (IDP) has been introduced in 2001. The programme is developed by the Department of Provincial and Local Government (DPLG) in order to be able to mediate between national, provincial and local priorities. In particular, the DPLG developed an Integrated Sustainable Rural Development Strategy (ISRDS) which combines and coordinates rural electrification with other poverty-relieving programmes, such as small-scale agriculture, cottage industries, social forestry, and education. This programme is supported in its implementation by the Independent

Development Trust (IDT). The ISRDP is organised in local councils, which set up economic and social projects with aid of government organisations and private investors. However, it is acknowledged that in order to attract private investments, the government has to provide a conducive environment that reduces risks and increases return on investments (IDT, 2006). The provision of basic infrastructure (notably electrification) is one such mechanism to attract more private investors.

As part of IDP, many rural areas will fall under jurisdiction of the local municipalities, which will have to develop rural development plans (Martens, de Lange et al. 2001:62). Secondly, municipalities will only receive funding for electrification programmes if they submit their projects through the IDP process (DME 2002:18). Since the concessionaires are established on national level and the IDP focuses on local level development, the concessionaires are explicitly linked to particular municipalities. Figure XX shows the relationship between the concessionaires and the municipalities in KwaZulu-Natal.

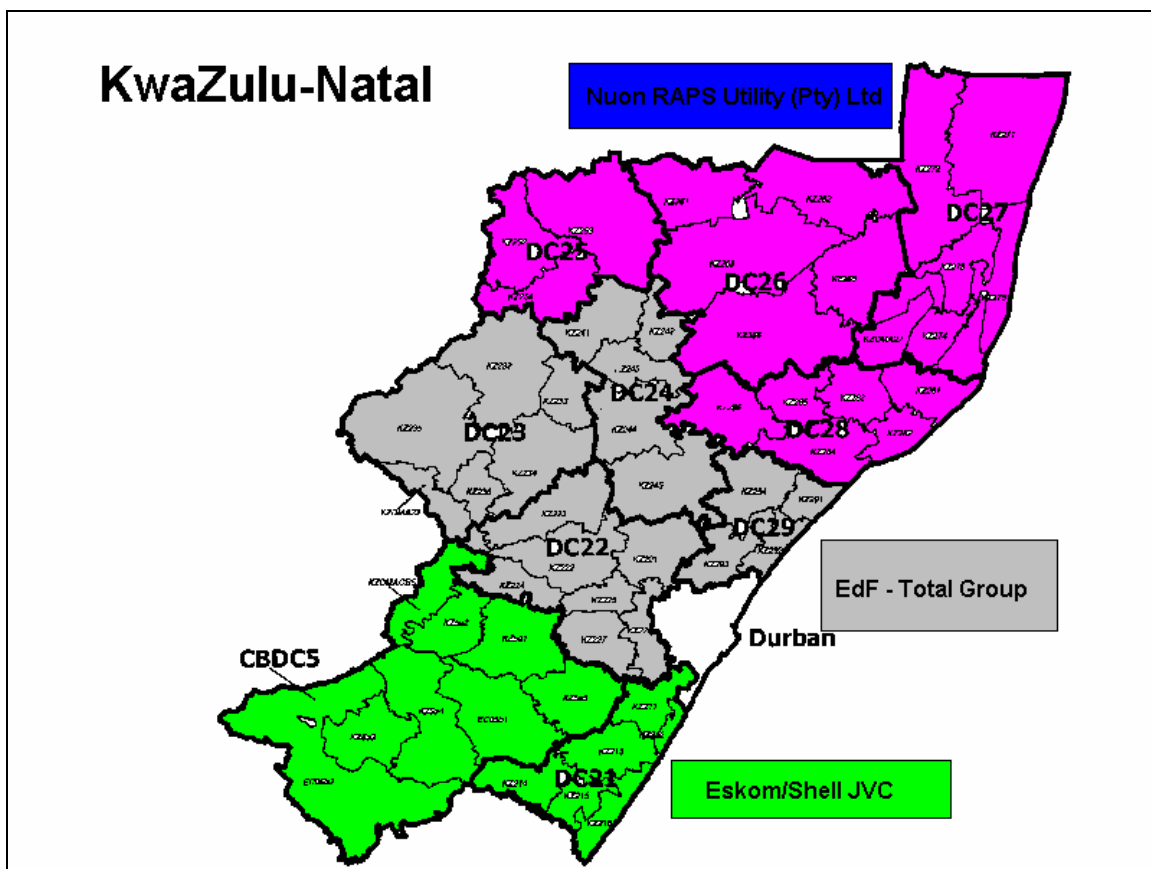


Figure A1- 3 Municipalities and their concessionaires in KwaZulu-Natal (DME 2001:33)

Within these political and regulatory frameworks, specific mechanisms have been suggested to promote the implementation of hybrid mini-grids, which would allow for more economic development in rural areas. It is suggested that the development of mini-grids is a responsibility from the concessionaires and that they should receive the same subsidies on capital expenditure of around R3000. Furthermore, there should be a guarantee fund to provide guarantees for the power purchase agreements and development should be integrated into the IDP (Martens, de Lange et al. 2001:109).

In March 2003, an overarching policy framework was established to incorporate the different individual programmes for water, road, building and electrification infrastructure. This framework, the Municipal Infrastructure Grant (MIG) falls under the responsibility of the DPLG. Currently, the DPLG provides the basic infrastructure needs for municipalities through the Consolidated Municipal Infrastructure Programme (CMIP), however this scheme will be phased out and the funds will be allocated directly to the municipalities under the MIG in 2006/2007 (DPLG 2004:3). From these MIG funds, around 20% needs to be earmarked for electrification (C&V Consulting Engineers 2006:1). The precise expenditure is the prerogative of each Local and District Municipality. The MIG allocation for 2006/2007 is given in table A1-1 in section A1.4.

A1.3 Renewable energy policies

The South African government published in 2003 a White Paper on Renewable Energy, which provided an renewable electricity target of 10 000 GWh in 2013 (DME 2003). However, it is unclear whether the target is cumulative or absolute. The DME reports states the following:

“To achieve this aim Government is setting as its target 10 000 GWh (0.8 Mtoe) renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and biofuels. *This is approximately 4% (1667 MW) of the projected electricity demand for 2013 (41539 MW).*”(DME 2003:1, original italics).

In this statement, the first sentence suggests that it is a cumulative target, while the last sentence suggests it is absolute.⁶⁸

A DME study in 2004 suggested that it is potentially possible to generate around 3031 GWh of electricity on the basis of bagasse residues in the sugar industry (DME 2004:6). Since 12 out of the 14 sugar mills producing bagasse are located in KwaZulu-Natal, it is interesting to see whether they would be able to provide an energy source for electricity production locally, fed into the grid or converted into biofuels which could be distributed locally either for the production of electricity locally or to burn directly. The study recommended bagasse as the most promising biomass source for the development of renewable energy projects (DME 2004:48).

In December 2005 a Biofuels Task Team was established in order to investigate the possibilities for a modest biofuel industry in South Africa (DME 2006). In terms of governmental instruments, the Minister of Finance has increased reduction in the fuel levy for biodiesel to 40% and the National Treasury has introduced accelerated depreciation for biodiesel (DME 2006). However, until now there are no explicit subsidies in place that promote the uptake of renewable resources, although there are some South African and international agencies that provide financial support (DME 2005).

The first draft report on the Biofuel Strategy of South Africa aims to achieve a biofuel average market penetration of 4.5% of liquid road transport fuels in 2013 (DME 2006). Strategies developed to encourage local biofuel production are three-fold; firstly biofuel producers can sell their products to a minimum of the Basic Fuel Price (BFP) to petroleum wholesalers. The BFP is the price a South African importer of petrol would have to pay to buy, ship and secure petroleum from overseas refineries (SASOL 2006). Secondly, if the price of oil goes below \$45/barrel, biofuel producers will receive fuel support of around 1.2 cents per liter via the Central Energy Fund (CEF) Act Equalization Fund Levy. Thirdly, the fuel levy exemption for biofuels of 40% still exist with a 100% exemption for small-scale producers (< 300 m³). Finally, the National Treasury released a Renewable Energy Subsidy Scheme, which amounts to a subsidy of 16.7 c/liter for bioethanol and 27.3 c/liter for biodiesel with a maximum of R 20 million (DME 2006).

⁶⁸ Telephone interviews suggest that Eskom has interpreted the target as cumulative, while DME officials interpret the target as absolute.

Since then, the biofuel market is slowly developing in South Africa. The first biodiesel reactor has been installed in November 2006 and there are further plans to develop biodiesel a generation capacity of 3411 million litres of biodiesel per year. Currently the feedstock for the biodiesel reactors is sunflower oil (Green Star 2006).

Another potential market for biofuels is as cooking fuel for remote households. The ‘Millenium Gelfuel Initiative’, shepherded by the World Bank in Africa, investigated the potential to replace current cooking fuels, such as wood and paraffin, with gel fuel on the basis of bioethanol (Utria 2004). Replacing the use of wood and/or paraffin with gel fuel has several advantages. In 2001 up to 100 000 paraffin related accidents cause fires, burns and deaths through the toxicity of paraffin, the explosive danger of paraffin burners and through indoor pollution and smoke. The use of wood cause patterns of destructive and unsustainable forestry resource exploitation. Furthermore, the use of woodfuels for cooking cause disproportionate health hazards for women and children (Utria 2004). Gel fuel is more effective, much safer and has less pollutants than paraffin or wood (Utria 2004; Visser 2004; Byrd and Rode 2005). Currently, a 200 000 litres/month gel fuel plant is operating in Durban, which uses bioethanol from sugar (Utria 2004). However, bioethanol from bagasse would be more beneficial to achieve both environmental and social goals (Farrell, Plevin et al. 2006).

A1.4 Electrification in KwaZulu-Natal

KwaZulu-Natal consists of 10 District Municipalities and 1 metropolitan municipality (ethekwini), which can be divided into Local Municipalities. These are shown in figure A1-4.



Figure A1- 4 Local Municipalities in KwaZulu-Natal (Statistics SA 2005:3)

In 2005, the constitution of South Africa has changed including the former Eastern Cape enclave of umzimkulu into the Kwazulu-Natal province. Umzimkulu is now part of Sisonke.

Kwazulu-Natal is particular suitable for off-grid solutions as there are often large distances to the grid, decreased settlement densities and difficulty of topography (INEP, 2002:m.8). Figure A1-5 shows the population density in Kwazulu-Natal.

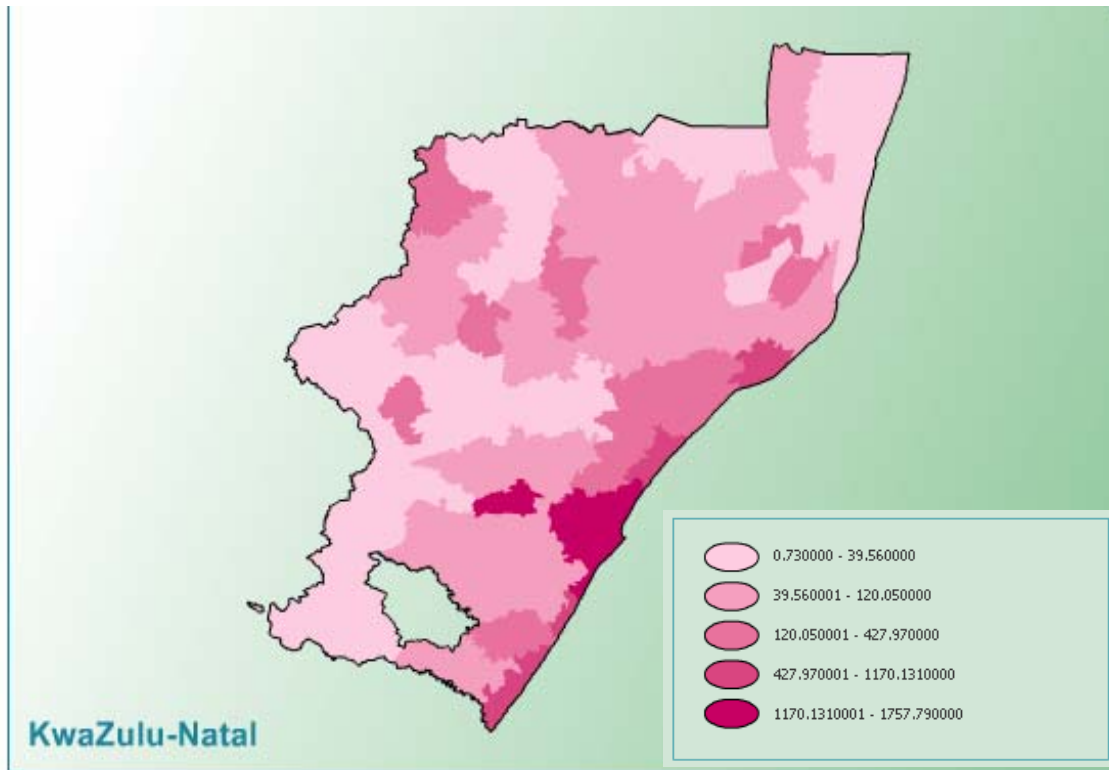


Figure A1- 5 Population density of KwaZulu-Natal (Statistics SA 2005)

In 2006/07 kwazulu-Natal was allocated R134 million for 21 0 20 Eskom household connections, which amounts to an average cost per connection of R6377. The total MIG allocation per municipality for 2006/07 is shown in table A1-1.

Table A1- 1 MIG allocation in KwaZulu-Natal (DPLG 2004)

Provincial Profile: KWAZULU-NATAL MIG Allocation		
WSA Name	WSA Code	Total0607
Amajuba District Municipality	DC25	14,938,128.00
eThekwini Metropolitan	Durban	142,699,235.00
iLembe District Municipality	DC29	62,148,474.00
Newcastle Municipality	KZ252	15,872,428.00
Sisonke District Municipality	DC43	33,000,249.00
The Msunduzi Municipality	KZ225	27,943,925.00
Ugu District Municipality	DC21	82,813,052.00
UMgungundlovu District Municipality	DC22	34,967,359.00
uMhlathuze Municipality	KZ282	17,487,774.00
Umkhanyakude District Municipality	DC27	63,763,408.00
Umzinyathi District Municipality	DC24	51,903,091.00
Uthukela District Municipality	DC23	61,251,338.00
Uthungulu District Municipality	DC28	66,874,188.00
Zululand District Municipality	DC26	80,050,524.00

If indeed 20% of the total MIG allocations (C&V Consulting Engineers 2006:1) would be allocated for electrification, the following capital is available for the district and metropolitan municipalities in Kwazulu-Natal:

Table A1- 2 Potential electrification allocations within the MIG for district and metropolitan municipalities in Kwazulu-Natal

Municipalities in Kwazulu-Natal	MIG electrification allocation
Amajuba District Municipality	2987625.6
eThekwini Metropolitan	28539847
iLembe District Municipality	12429694.8
Newcastle Municipality	3174485.6
Sisonke District Municipality	6600049.8
The Msunduzi Municipality	5588785
Ugu District Municipality	16562610.4
UMgungundlovu District Municipality	6993471.8
uMhlathuze Municipality	3497554.8
Umkhanyakude District Municipality	12752681.6
Umzinyathi District Municipality	10380618.2
Uthukela District Municipality	12250267.6
Uthungulu District Municipality	13374837.6
Zululand District Municipality	16010104.8

In terms of non-grid electrification, KwaZulu-Natal received mR 35 in 2004/05 with a further mR 38 in 2006/07. However, no scheduling of non-grid projects were done up till

2005. In 2002/03 and 2003/04, Kwazulu-Natal connected respectively 31506 and 35536 households to the grid with average connection costs of R6250 per household. The subsidies for either grid or non-grid connections received in 2004/05 were respectively R5438 and R4500, favouring the more expensive grid connections (C&V Consulting Engineers 2006:16). Therefore, there have been only a limited number of non-grid projects in KwaZulu-Natal. The connection costs for grid seem to increase over time and are up to 40% more expensive than the national average costs (C&V Consulting Engineers 2006:8).

A case-study on electricity use in two peri-urban settlements in Kwazulu-Natal showed that their average monthly electricity expenditure was around R26-65 using on average between kWh 68-170 (Davidson and Mwakasonda 2004:18). A survey in the Eastern Cape on the energy consumption of two unelectrified villages showed an average monthly expenditure on paraffin, candles and lpg of respectively R 68, 19, 135, which would be an equivalent expenditure of R52/month on electricity (Scottish Power 2003:30). In comparison, a mini-grid, grid connections or solar home systems could provide the electricity service (if the capital expenditures are 100% subsidised) for respectively R 38, 24 and 18.

In 2006 the Amajuba District in KwaZulu-Natal developed an Electricity Service Delivery Plan (ESDP) to inform the IDP. The following criteria were developed for grid and non-grid connections:

For grid connections, the area should:

- contain bulk supply lines and have a density of 50 consumers/km²
- border bulk supply lines and have a density of 100 consumers/km²
- have connection costs lower than R6720 (C&V Consulting Engineers 2006:16).

For non-grid or mini-grid connections, Scottish Power used the following criteria: .

- no grid electrification plans for at least 5 years
- density of 50 consumers/km²
- alignment of community expectation as well as potential institutional users (schools, clinics and others)
- isolated villages (Scottish Power 2003:7).

A1.5 Biofuels in KwaZulu-Natal

With current petrol use of 70 million liters per day in KwaZulu-Natal and an annual growth of 4% (Coetzee 2006) and a proposed penetration of 4.5% of the total petrol use in 2013 (DME 2006), the potential market demand for bioethanol in KwaZulu-Natal is quite large. For the initial situation in Kwazulu-Natal, this would imply a total market of 3.15 million liters of bioethanol per day.

Bioethanol can also be converted to gelfuel to replace paraffin as cooking fuel in households. There are several positive social benefits for gelfuel in terms of safety, the reduction of respiratory women an children and the reduction of labour required to gather wood fuel (Utria 2004; Byrd and Rode 2005). Biodiesel has two potential applications. Firstly, it could be used as an energy source in transport or for appliances in the agricultural sector (ie tractors or stand-alone electricity generators. Secondly, it can be used as an energy fuel for the development of local minigrids on the basis of fuel engines. These engines can be build in modules of 5, 7,5 and 10 MW with a total upper limit of 40 MW in capacity (Bridgwater, Toft et al. 2002:207). A description of these technologies and their associated costs can be found in appendix A2.

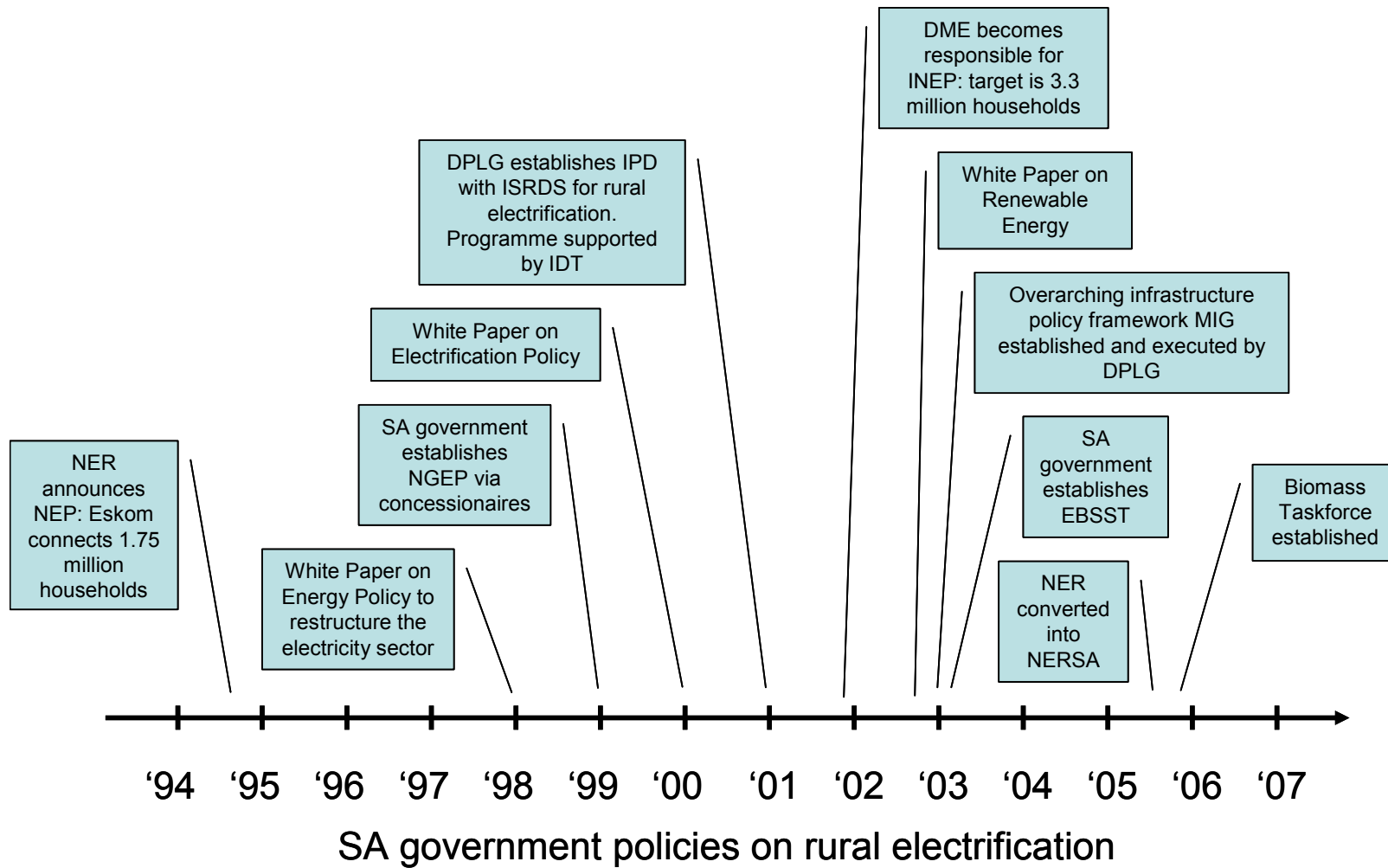


Figure A1- 6 Simplified overview of SA government policies on rural electrification

A1.6 Modelling rural electrification

The information provided shows that the municipalities have several options in order to provide rural electrification. From a technical perspective, there are the following options on the basis of bagasse as biomass source:

1. Decentralised electricity production: local electricity production at the sugar mills, whereby the electricity is fed into the existing grid.
2. Centralised electricity production: electricity production either by cofiring at the existing coal-fired power plant from Eskom or a centralised electricity production by an independent power producer in Durban.
3. Centralised bioethanol production: via enzymatic hydrolysis or pyrolysis in a centralised production plant in Durban. The bioethanol can be used either to blend into transport fuels to achieve the biofuel target of 4.5% in 2013 or to produce gel fuel in order to replace paraffin and wood for cooking and heating, therefore reducing fire hazard and the reducing presperous diseases
4. Centralised bioethanol production: via enzymatic hydrolysis or pyrolysis in a centralised production plant in Durban. The fuel can be used to produce electricity for mini-grid via fuel engines. As such, rural areas can be electrified providing electricity for lightning, media and potentially cooking and heating purposes.

All these options can be evaluated on the basis of a life cycle cost basis as recommended in the INEP. Furthermore, the costs are influenced by the population density within the municipality, the total number of unelectrified households available, the MIG allocations and the subsidies awarded to grid and non-grid connections. Furthermore, data is required about the proximity of major supply lines in the municipalities. The criteria in Amajuba's Electricity Service Delivery Plan (ESDP) will be used as general guidelines, thus for grid connections the local municipality should:

- contain bulk supply lines and have a density of 50 consumers/km²
- border bulk supply lines and have a density of 100 consumers/km²
- have connection costs lower than R6720 (C&V Consulting Engineers 2006:16).

The specifics for each municipality are presented in the appendix. It should be noted that the appendix only gives the initial density figures and non-electrification numbers for the

municipalities. As the model runs, these figures will be updated depending on population growth and electrification. The subsidy received for grid and non-grid connections will be respectively R5438 and R4500 (C&V Consulting Engineers 2006:16).

In terms of decision making, there are two major players. For grid connections, the district municipalities can make decisions on how they allocate their electrification budget to the different local municipalities in order to establish grid connections. However, some local municipalities have been allocated MIG funds or other electrification funds directly. In the model this will be incorporated as if district municipalities have allocated these funds to local municipalities (see the Amajuba project). For non-grid connections, the concessionaires can use their budget to establish non-grid connections in the least cost municipalities in their allocated areas.

A1.7 Demographical and geographical Information on local governments and municipalities

For each of the provinces and municipalities, the following demographical and geographical information was collected:

1. Location of local municipalities within district municipalities
2. Location of powerlines and non-grid power substations in local and district municipalities
3. Population, number of (electrified and unelectrified) households, surface area, operational and capital budget for electrification per local and district municipality.

All data is provided by SA Statistics on the basis of the 2001 Census with updates in 2005 (Statistics SA 2005). The following sections refer to the electrification data in the following provinces:

A1.7.1.: Ugu

A1.7.2: Umgungundlovu

A1.7.3: Uthukela

A1.7.4: Umzinyathi

A1.7.5: Amajuba

A1.7.6: Zululand

A1.7.7: Umkhanyakude

A1.7.8: Uthungulu

A1.7.9: Ilembe

A1.7.10: Sisonke

A1.7.1 Ugu

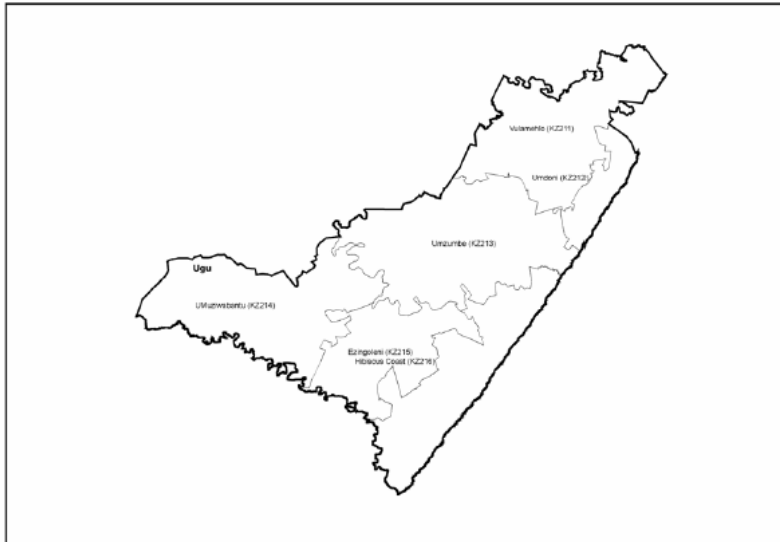


Figure A1- 7 Local municipalities in Ugu

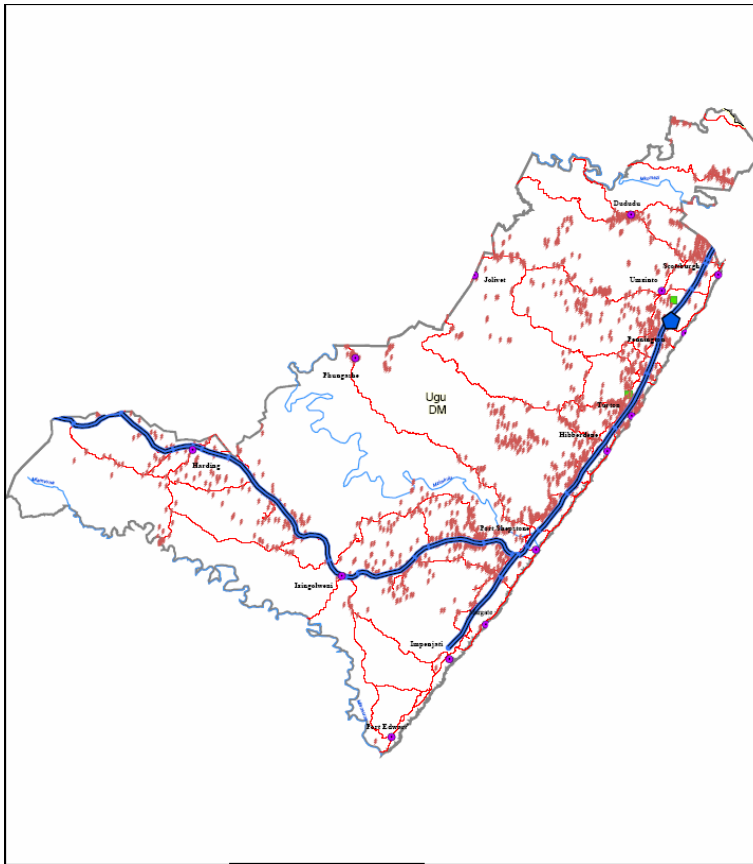


Figure A1- 8 Powerlines (black) and substations (brown) in Ugu

Table A1- 3 Household density, electrification budgets in Ugu

name	ugu	ivulamehlo	umdoni	umzumbe	umuziwabantu	ezingoleni	hibiscuscoast
population	704028	83044	62293	193767	92327	54428	218169
households	150613	15807	15288	38281	19088	10684	51465
people per household	4.7	5.3	4.1	5.1	4.8	5.1	4.2
area		973.2	238.1	1258.9	1089.5	648.1	839.0
density		16.2	64.2	30.4	17.5	16.5	61.3
electrification	72355	3108	10106	11112	5083	4002	38944
unelectrified	52.0	80.3	33.9	71.0	73.4	62.5	24.3
operating budget	0	0	0	0	9577900	0	2990000
budget per household	0	0	0	0	502	0	58
budget per elec. Household	0	0	0	0	1884	0	77
MIG allocation electrification	16562610.4	0	0	0	0	0	0
capital per connection	211.6	0	0	0	0	0	0
powerlines	no	no	no	no	no	no	no

A1.7.2 Umgungundlovu

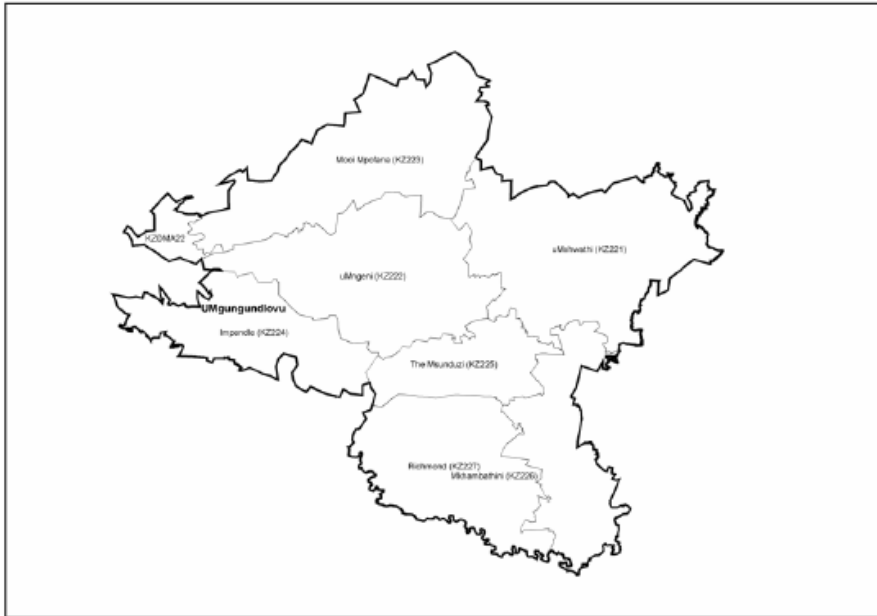


Figure A1- 9 Local municipalities in Umgungundlovu

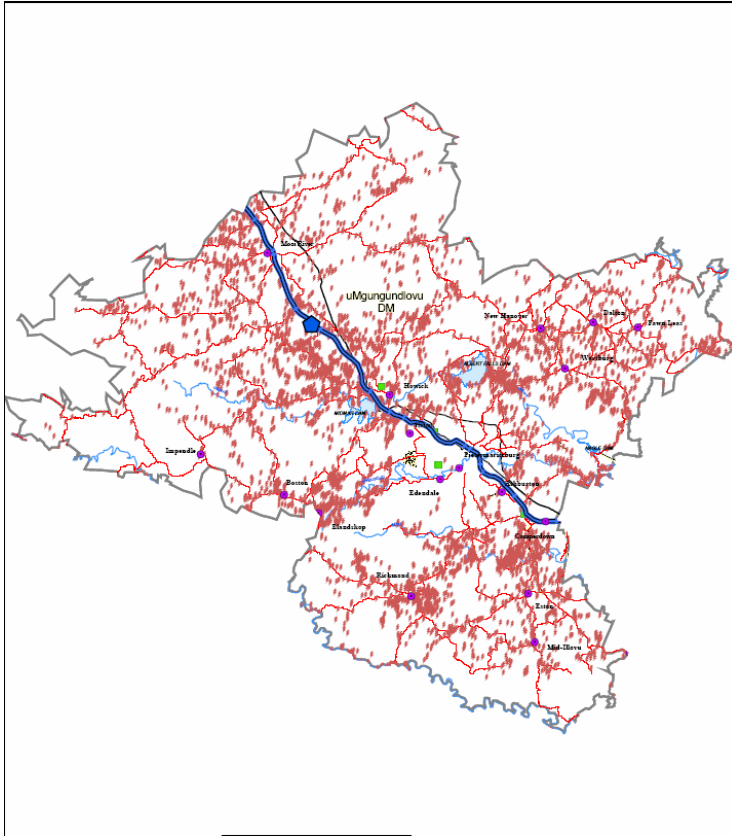


Figure A1- 10 Powerlines (black) and substations (brown) in Umgungundlovu

Table A1- 4 Household density, electrification budgets in Umgungundlovu

name	umgungundlovu	umshwathi	umngeni	mooimpofana	impindle	msunduzi	mkhambathini	richmond
population	927845	108037	73896	36819	33569	553223	59067	63222
households	216646	23737	20487	9597	7344	130387	12551	12533
people per household	4.3	4.6	3.6	3.8	4.6	4.2	4.7	5.0
area		1817.9	1566.5	1651.6	948.7	633.8	915.4	1231.3
density		13.1	13.1	5.8	7.7	205.7	13.7	10.2
electrification	161098	12591	15153	5124	4486	111655	5329	6753
unelectrified	25.6	47.0	26.0	46.6	38.9	14.4	57.5	46.1
operating budget	0	0	29796781	9905294	0	511748504	0	0
budget per household	0	0	1454	1032	0	3925	0	0
budget per elec. Household	0	0	1966	1933	0	4583	0	0
MIG allocation electrification	\$6,993,471.8	\$0.0	\$0.0	\$0.0	\$0.0	\$5,588,785.0	\$0.0	\$0.0
capital per connection	\$125.9	\$0.0	\$0.0	\$0.0	\$0.0	\$298.4	\$0.0	\$0.0
powerlines		no	yes	yes	no	yes	no	no

A1.7.3 Uthukela



Figure A1- 11 Local municipalities in Uthukela

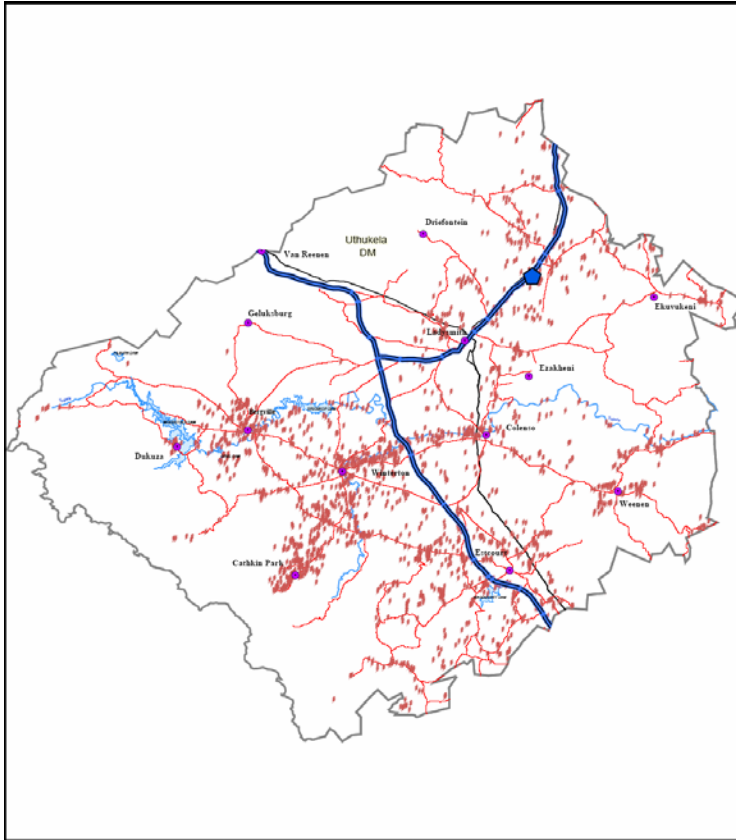


Figure A1- 12 Powerlines (black) and substations (brown) in Uthukela

Table A1- 5 Household density, electrification budgets in Uthukela

name	uthukela	emnambithi	indaka	umtshezi	okhahlamba	imbabazane
population	656986	225459	113644	59921	137525	119925
households	134847	50528	21372	13093	26678	23032
people per household	4.9	4.5	5.3	4.6	5.2	5.2
area		2964.8	991.5	2130.3	3475.5	827.3
density		17.0	21.6	6.1	7.7	27.8
electrification	77664	34137	10009	8233	10361	14809
unelectrified	42.4	32.4	53.2	37.1	61.2	35.7
operating budget	0	84759072	0	44044327	0	0
budget per household	0	1677	0	3364	0	0
budget per elec. Household	0	2483	0	5350	0	0
MIG allocation electrification	12250267.6	0.0	0.0	0.0	0.0	0.0
capital per connection	214.2	0.0	0.0	0.0	0.0	0.0
powerlines		yes	no	yes	no	no

A1.7.4 Umzinyathi

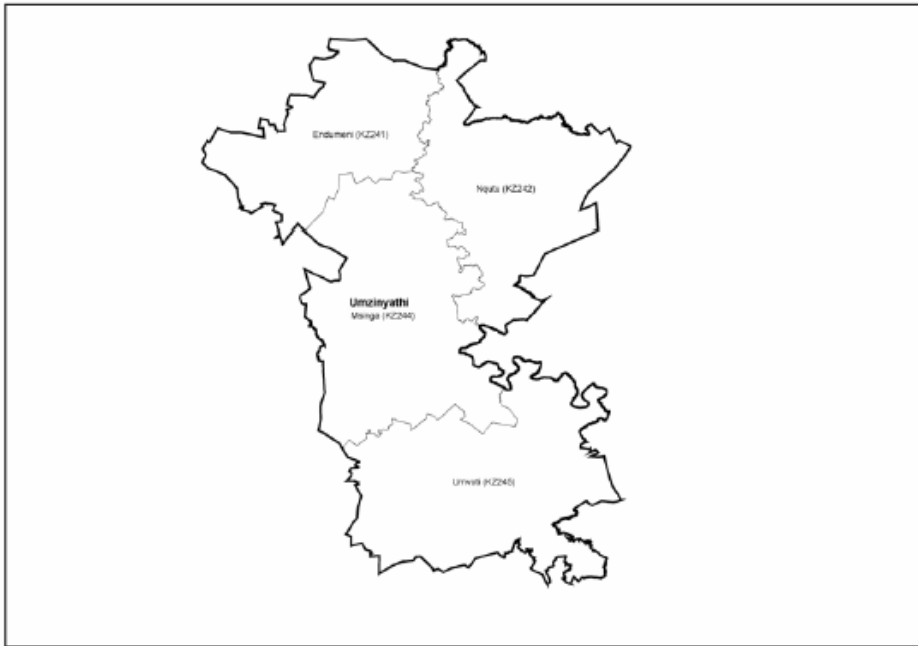


Figure A1- 13 Local municipalities in Amajuba

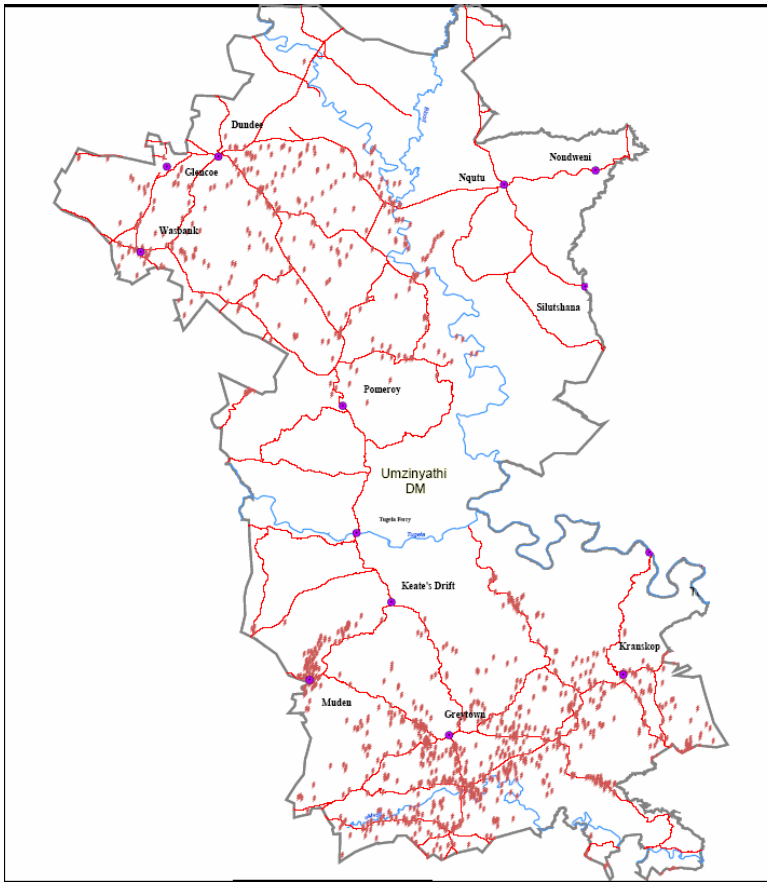


Figure A1- 14 Powerlines (black) and substations (brown) in Umzinyathi

Table A1- 6 Household density, electrification budgets in Umzinyathi

name	umzinyathi	endumeni	nqutu	msinga	umvoti
population	456455	51101	145034	168026	92294
households	90108	12279	25653	32506	19670
people per household	5.1	4.2	5.7	5.2	4.7
area		1610.3	1961.8	2501.2	2515.6
density		7.6	13.1	13.0	7.8
electrification	21871	8145	4307	2682	6737
unelectrified	75.7	33.7	83.2	91.7	65.7
operating budget	0	0	3430510	8730000	121137532
budget per household	0	0	134	269	6158
budget per elec. Household	0	0	796	3255	17981
MIG allocation electrification	10380618.2	0.0	0.0	0.0	0.0
capital per connection	152.1	0.0	0.0	0.0	0.0
powerlines		no	no	no	no

A1.7.5 Amajuba



Figure A1- 15 Local municipalities in Amajuba

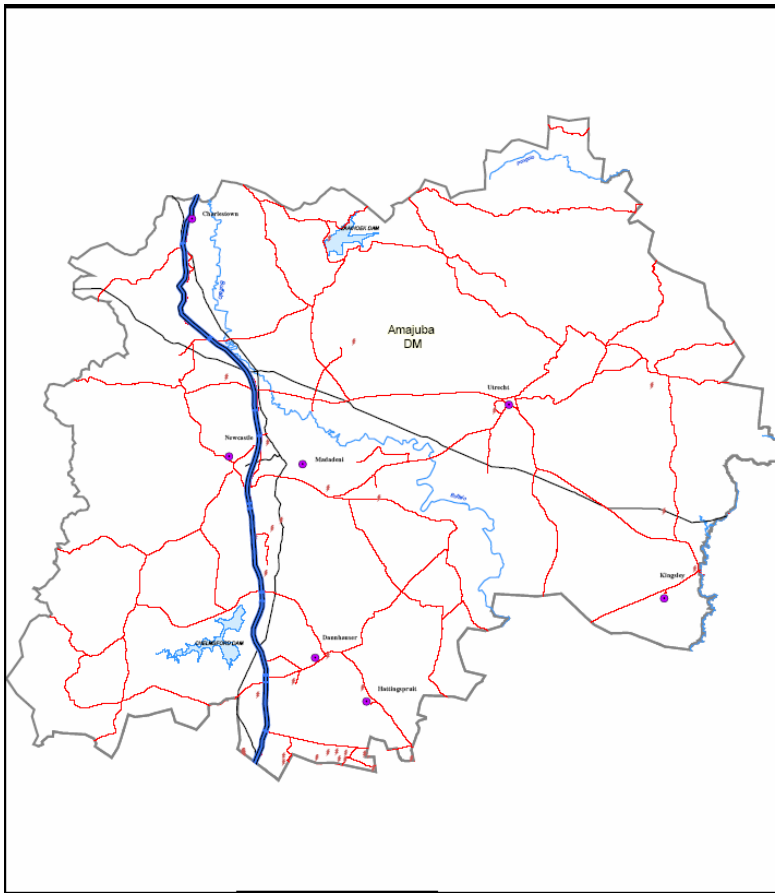


Figure A1- 16 Powerlines (black) and substations (brown) in Amajuba

Table A1- 7 Household density, electrification budgets in Amajuba

name	amajuba	newcastle	utrecht	dannhauser
population	468037	332981	32277	102779
households	96672	71165	6187	19320
people per household	4.8	4.7	5.2	5.3
area		1855.3	3539.3	1515.8
density		38.4	1.7	12.7
electrification	70084	59884	1801	8399
unelectrified	27.5	15.9	70.9	56.5
operating budget	100000	135613699	3934558	0
budget per household	1	1906	636	0
budget per elec. Household	1	2265	2185	0
MIG allocation electrification	2987625.6	3174485.6	0	0
capital per connection	112.4	281.4	0.0	0.0
powerline		yes	yes	no

A1.7.6 Zululand



Figure A1- 17 Local municipalities in Zululand



Figure A1- 18 Powerlines (black) and substations (brown) in Zululand

Table A1- 8 Household density, electrification budgets in Zululand

name	zululand	edumbe	uphongolo	abaqulusi	nongoma	lulundi
population	804454	82241	119780	191019	198444	212970
households	144951	15106	24814	35913	31578	37540
people per household	5.5	5.4	4.8	5.3	6.3	5.7
area		1942.8	3239.2	4184.6	2182.1	3250.7
density		7.8	7.7	8.6	14.5	11.5
electrification	55414	4723	13280	15498	7766	14147
unelectrified	61.8	68.7	46.5	56.8	75.4	62.3
operating budget	0	4859869	7941209	50668433	0	23316193
budget per household	0	322	320	1411	0	621
budget per elec. Household	0	1029	598	3269	0	1648
MIG allocation electrification	16010104.8	0.0	0.0	0.0	0.0	0.0
capital per connection	178.8	0.0	0.0	0.0	0.0	0.0
powerlines		no	no	no	no	no

A1.7.7 Umkhanyakude



Figure A1- 19 Local municipalities in Umkhanyakude

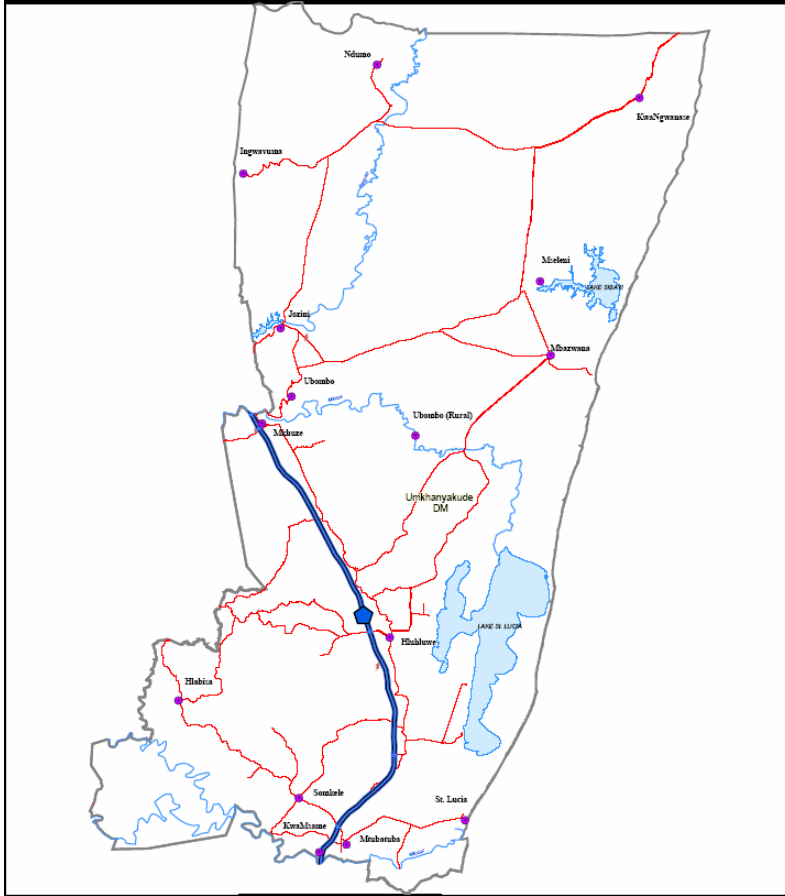


Figure A1- 20 Powerlines (black) and substations (brown) in Umkhanyakude

Table A1- 9 Household density, electrification budgets in Umkhanyakude

name	umkhanyakude	umhlabuyalingana	jozini	big5falsebay	hlabisa	mtubatuba
population	573341	140962	184090	31106	176890	35211
households	101566	25961	33547	6152	26877	7835
people per household	5.6	5.4	5.5	5.1	6.6	4.5
area		3619.1	3056.2	1060.8	1417.3	496.5
density		7.2	11.0	5.8	19.0	15.8
electrification	20380	1662	3481	1103	7639	5882
unelectrified	79.9	93.6	89.6	82.1	71.6	24.9
operating budget	1606748	0	0	0	0	0
budget per household	16	0	0	0	0	0
budget per elec. Household	79	0	0	0	0	0
MIG allocation electrification	12752681.6	0.0	0.0	0.0	0.0	0.0
capital per connection	157.1	0.0	0.0	0.0	0.0	0.0
powerlines		no	no	no	no	no

A1.7.8 Uthungulu

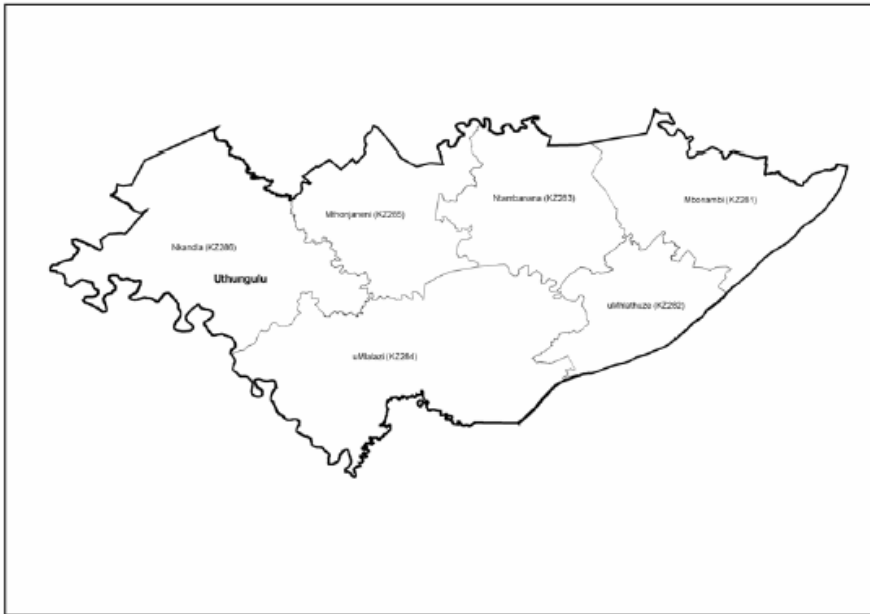


Figure A1- 21 Local municipalities in Uthungulu

A1.7.9 Ilembe



Figure A1- 23 Local municipalities in Ilembe

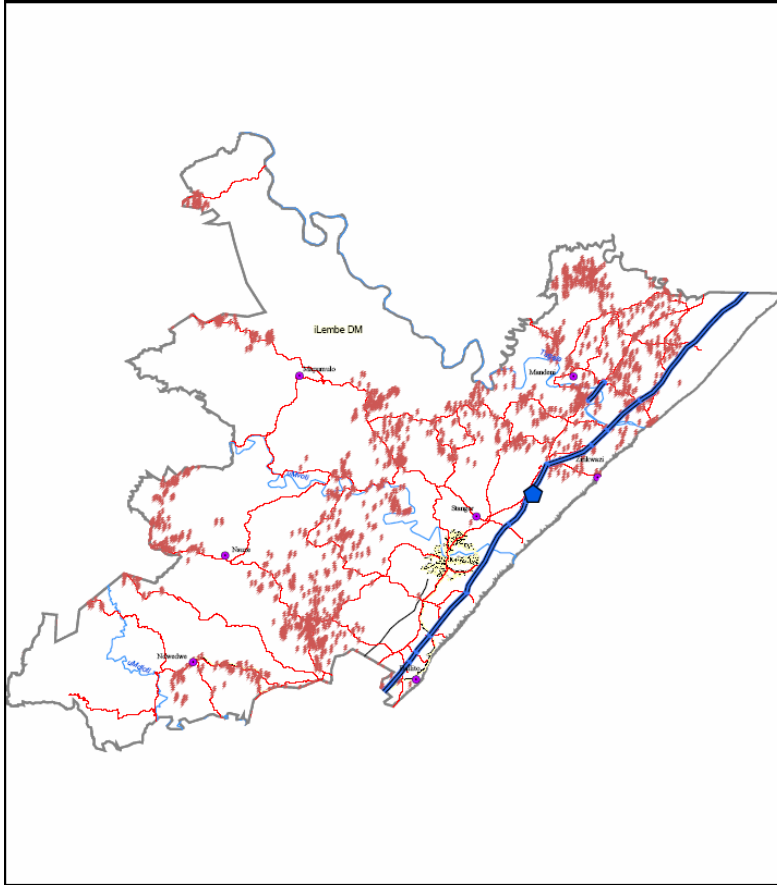


Figure A1- 24 Powerlines (black) and substations (brown) in Ilembe

Table A1- 11 Household density, electrification budgets in Ilembe

name	ilembe	endondakusuka	kwadukuza	ndwedwe	maphumulo
population	560388	128669	158582	152495	120642
households	120390	28952	41709	27580	22149
people per household	4.7	4.4	3.8	5.5	5.4
area		582.2	633.1	1157.4	895.9
density		49.7	65.9	23.8	24.7
electrification	59337	18111	31533	5932	3761
unelectrified	50.7	37.4	24.4	78.5	83.0
operating budget	0	5393240	131987678	0	1218796
budget per household	0	186	3164	0	55
budget per elec. Household	0	298	4186	0	324
MIG allocation electrification	12429694.8	0.0	0.0	0.0	0.0
capital per connection	203.6	0.0	0.0	0.0	0.0
powerlines		no	yes	no	no

A1.7.10 Sisonke



Figure A1- 25 Local municipalities in Sisonke

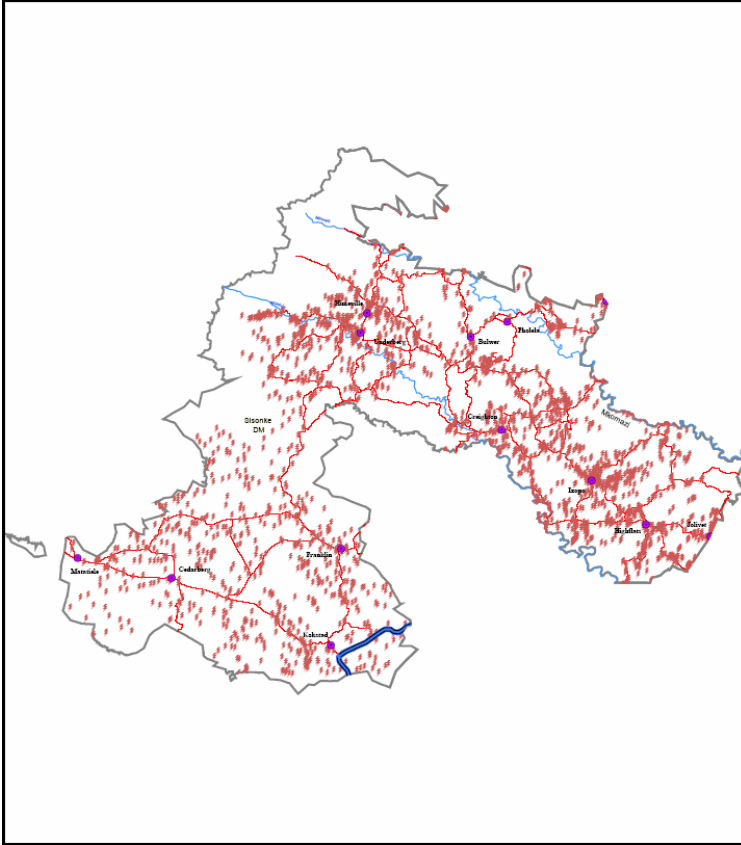


Figure A1- 26 Powerlines (black) and substations (brown) in Sisonke (excl. umzimkhulu)

Table A1- 12 Household density, electrification budgets in Sisonke

name	sisonke	umzimkhulu	ingwe	kwasani	kokstad	ubuhlebezwe
population	298394	174339	107558	15309	56528	101959
households	72239	36246	21332	4415	19625	21420
people per household	4.1	4.8	5.0	3.5	2.9	4.8
area		2435.4	1991.3	1212.8	2679.8	1604.1
density		14.9	10.7	3.6	7.3	13.4
electrification	25788	11224	5744	1606	9818	5595
unelectrified	64.3	69.0	73.1	63.6	50.0	73.9
operating budget	0	0	0	0	30518615	0
budget per household	0	0	0	0	1555	0
budget per elec. Household	0	0	0	0	3108	0
MIG allocation electrification	6600049.8	0.0	0.0	0.0	0.0	0.0
capital per connection	142.1	0.0	0.0	0.0	0.0	0.0
powerlines		no	no	no	no	no

A1.8 References

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Modelling data for investment decisions in energy technologies

A2.1 Introduction

The case study of an industrial biomass energy network in an eastern province of South Africa, KwaZulu-Natal, is used to apply the modelling approach for the design of industrial networks. The case study centres around the use of biomass sources to produce green electricity. Twelve independent sugar factories have bagasse as a waste product from sugar processing of sugarcane. Bagasse is the fibrous material left over after pressing out the sugar-rich juice with a high moisture content of around 50 wt% (Erlich, Ohman et al. 2005)⁶⁹. The bagasse has a reported gross calorific value of 9.9 Mj/kg (Beeharry 1996:444), however DME (2004) reports a value of 7.1 Mj/kg for South Africa's bagasse (DME 2004:31). The bagasse is currently burned inefficiently in boilers with a thermal efficiency around 62%⁶⁹ to fulfil local heat requirements within the plant (Rasul and Rudolph 2000:123). Even when the mill's energy requirements are fulfilled, it is not uncommon to have about 15 – 25% excess bagasse, which in some cases is sold to the pulp and paper industry as an alternative for wood (Kadam 2000:7). The price that sugar mills receive is on the basis of a reimbursement that the sugar mills receive for the energy value of the fibrous bagasse. In South Africa, the price paid for bagasse is around 31.4 ZAR/tonne of bagasse⁷⁰ (Mkhize 2005), while the average value per tonne bagasse in Argentina is 78 ZAR/tonne (Castillo 1992:426). Also in Argentina, these

⁶⁹ In comparison, standard industrial boilers have efficiencies up to 80% Kadam, K. L. (2000). Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay). Golden, Colorado, National Renewable Energy Laboratory: 1-31.p. 31

⁷⁰ Calculation for bagasse price: 250R/t coal * 1t coal/3.5 t fibre * 0.44t fibre/t bagasse = 31.4R/t bagasse

charges are based on the basis of the costs to produce the same amount of energy using an alternative fuel than bagasse (most commonly gas) in the sugar mills boilers.

The sugar factories have the opportunity to improve their boiler efficiencies and use the excess bagasse to produce green electricity, which is currently sold for 250 ZAR/MWh (DME 2004). Beeharry (1996) reports that for every tonne of millable cane almost 300 kg of bagasse (50 wt% moisture) is potentially available for exportable electricity production in region of 60 to 180 KWh (Beeharry 1996:441). However, such a strategy would involve substantial investments in an uncertain market. Furthermore, it involves strategic issues such as the choice of technology (pelletising, combustion versus gasification) and the production capacity. A potential client or competitor of the sugar factories is the existing electricity generator, who has interests in purchasing bagasse from the sugar factories to produce its own green electricity. Furthermore, independent power producers are entering the South African electricity markets, which can be potential buyers of bagasse or competitors for both the sugar industries and the existing electricity generator. In terms of non-industrial organizations, there are several governmental organizations that have different objectives, such as meeting national environmental targets, supplying cheap electricity to rural areas and providing employment for local workers. These governmental organizations affect the evolution of the network through the supply of information and subsidies and the implementation of regulation.

However, an alternative for producing electricity from bagasse is the production of bioethanol or bioliquids. These fuels have as advantage that it can be stored and distributed within unelectrified regions in KwaZulu-Natal. Illovo, one of the two major sugar companies in KwaZulu-Natal, sums up the following advantages for the bioethanol production from sugarcane bagasse:

- health benefits
- safety benefits
- environmental benefits
- social benefits
- foreign exchange benefits with high bioethanol demands in Europe
- development of locally based industries for fuel and stoves (Tomlinson 2004:8).

The last point refers to the use of bioethanol or bioliquids as a local energy source for electricity generation in small-scale generation plants or as an alternative for paraffin or gas used for cooking and heating purposes. Bioethanol can also be used as a transport medium replacing the use of petrol. Sugar factories could either install these technologies themselves or independent producers of bioethanol could enter the market.

A2.2 Data requirements and analysis

The following technology options exist for the introduction of a biomass energy network in KwaZulu-Natal:

- Pelletising of bagasse
- Combustion of raw/pelletised bagasse for the production of electricity
- Gasification of raw/pelletised bagasse for the production of electricity
- Co-firing of raw/pelletised bagasse in coal-fired power plants
- Physiochemical conversion of raw bagasse into bioethanol
- Biological conversion of raw bagasse into bioethanol
- Storage facilities for bioethanol/bioliquids
- Technologies for decentralised generation of electricity from bioethanol/pyrolysis liquids
- Connection to the grid
- Rural electrification (from grid and non-grid)
- Transport technologies

The last technologies in this list are so called ‘supportive’ technologies, which are required for the practical implementation of a biomass energy network. These supportive technologies consist of road and/or rail transport technologies for bagasse and bioethanol. Furthermore, transmission and distribution networks are required to supply electricity from the location of generation to households and other electricity users.

The following data is required in order to describe the technology’s attributes⁷¹ and to model their potential take-up within a future biomass energy network:

⁷¹ The term ‘attributes’ is used, because it refers in decision analysis to those characteristics that can be used to determine the utility of an alternative. See for example: Keeney, R. L. and T. McDaniels (2000). Value-Focused Thinking about Strategic Decisions at BC Hydro. Judgement and Decision Analysis. T.

- feedstock characteristics
- product characteristics
- capital costs
- operational costs
- economies of scale
- energy use
- emissions
- capacity limitations
- efficiency
- production time
- learning curve

A2.2.1 Data uncertainty

For some technologies, there is a large variety in the characteristics quoted by different sources. This uncertainty in the data available can affect the outcome of the models. On the other hand, the uncertainty is an intrinsic part of industrial networks and should therefore be incorporated into the models. However, instead of developing a methodology to deal with the uncertainty in the input data, it is more important to model how the organisations deal with the uncertainty in the numbers in their decision making processes. Namely, it is exactly the way in which they incorporate the uncertainty into their decision making that affects the evolution of the network. The outcome of the decision rules that determine ‘how to deal’ with uncertainty affects the decisions, not the uncertainty itself. For example, an organisation that bases its decisions on the basis of the most pessimistic data found can make a different decision than an organisation that relies on the mean data points.

Each organisation can have different decision rules about how to deal with uncertainty, which can affect their decision outcomes. This is discussed in more detail in chapter 5. For the technical data, it is assumed that all organisations derive data on the basis of multiple sources and that they use the best fit (or mean) of the data sets. Any other assumptions are made explicit in the descriptions.

A2.3 Literature study

An extensive literature study in both academic as well as open source literature has been carried out in order to find data to characterise the technology options available for the introduction of a biomass energy network in KwaZulu-Natal. Since the case study is located in South Africa, all the economic data will be converted to South African Rand (ZAR)⁷². This section will start with a couple of overview data for different technologies, after which each technology option will be discussed in more detail separately.

A2.3.1 Overview studies for biomass conversion

Mitchells et al. (1995) reports on the techno-economic assessment of different electricity generation options for biomass (wood with a moisture content of 53.9 wt%), which is quite similar to using raw bagasse:

- atmospheric gasification (generic gasifier, wet gas scrubbing, dual fuel engine)
- pressure gasification (generic gasifier, hot gas filtration, gas turbine combined cycle)
- fast pyrolysis (pyrolyser, oil storage, pilot-injected diesel engine)
- combustion (fluid bed combustor steam turbine).

Techno-economic characteristics of these technologies are given in the next table:

⁷² FX Converter, www.oanda.com/convert, 9 october 2006. 1 US\$ = 7.88 ZAR, 1 EURO = 9.87 ZAR, 1 GBP = 14.5 ZAR.

Table A2- 1 Technical and financial characteristics of electricity generation options for biomass (Mitchell, Bridgwater et al. 1995:210)

	units	pyrolysis	gasification	IGCC	combustion
power output	MW	20	20	20	20
overall efficiency	% LHV	29.8	27.6	37.9	23.5
wood transported as		chips	chips	chips	chips
delivered moisture content	wet basis	53.9	53.9	53.9	53.9
feed produced	odt/yr	92861	97739	79129	127566
feed delivered	odt/yr	91245	96039	77752	125346
feed to reactor	odt/yr	89784	94500	76507	123338
plantation area	ha	64057	67423	54585	87998
wood transport distance	km	31.9	32.8	29.5	37.4
delivery period	m/yr	12	12	12	12
delivered feed cost	ZAR/odt	377.4	379.1	372.2	389.0
spec cap cost, total	mZAR/MW	19.6	21.8	30.1	23.1
electricity production cost	ZAR/MWh	740.7	756.5	803.8	851.0
generating period	m/yr	12	12	12	12
generating hours	h/d	24	24	24	24
conversion availability	%	90	90	90	90
genset maintenance cost	ZAR/MWh	78.8	78.8	59.1	98.5
maintenance costs plant	% capital cost/yr	2.5	2.5	2.5	2.5
overheads	% capital cost/yr	2.5	2.5	2.5	2.5
life of project	yr	20	20	20	20

Each technology displays economies of scale. The capital costs and system efficiencies for different capacities (5, 20, 50 and 100 MW) for the four technologies are as follows:

Table A2- 2 Economies of scale for electricity generation options for biomass (Mitchell, Bridgwater et al. 1995:213)

		pyrolysis	gasification	IGCC	combustion
overall efficiency (% LHV)	5 MW	25.8	24.8	22.5	18
	20 MW	29.8	27.6	37.9	23.5
	50 MW	32.8	28.8	45	26
	100 MW	34	30.5	48	29
difference in capital costs from standard 20MW (%)	5 MW	50%	50%	50%	50%
	20 MW	0	0%	0%	0%
	50 MW	5%	-10%	-10%	-10%
	100 MW	-15%	-15%	-15%	-15%
elect. Prod. costs (ZAR/MWh)	5 MW	1063.8	1119.0	1560.2	1355.4
	20 MW	740.7	756.5	803.8	851.0
	50 MW	638.3	685.6	622.5	709.2
	100 MW	622.5	638.3	567.4	654.0

Bridgwater & Brammer (2002) compares four different technologies:

- combustion with a Rankine steam cycle
- gasification with a gas-fired fuel diesel engine

- gasification with a gasturbine combined cycle
- fasy pyrolysis with a gas-fired fuel diesel engine .

The following overall efficiencies, capital costs and operational costs were reported (Bridgwater, Toft et al. 2002:232):

Table A2- 3 Efficiencies and operational- and capital costs of biomass conversion technologies (Bridgwater, Toft et al. 2002:238)

capacity MW	Combustion			IGCC			gasEng			pyrEng		
	efficiency** (%)	capital cost (mZAR/MW)	opex* (zar/MWh)	efficiency** (%)	capital cost (mZAR/MW)	opex* (zar/MWh)	efficiency** (%)	capital cost (mZAR/MW)	opex* (zar/MWh)	efficiency** (%)	capital cost (mZAR/MW)	opex* (zar/MWh)
1	12.5	48.9	1244	28	93.8	2290	26	63.2	1915	24	48.9	1599
2	15	37.0		32	69.6		27	49.8		24.5	39.2	
6	18.5	24.7	592	37	47.4	1046	27.5	37.5	948	25	28.1	829
10	21.5	20.2		39	39.0		28	31.1		25.5	24.7	
20	24	18.8	411	43	30.1	730	32	29.1	711	27.5	20.7	667

* operational costs include maintenance, overheads, utilities, labour and amortisation

** on the basis of 30 wt% moisture content

Table A2- 4 Capital and operational costs for pyrolysis and decentralised electricity generation with dual-fuel engine fuel injection system (Bridgwater, Toft et al. 2002:235)

capacity MW	Pyrolysis		Decentralised electricity generation	
	capital cost (mZAR/MW)	opex* (zar/MWh)	capital cost (mZAR/MW)	opex* (zar/MWh)
1	22.1	1349	26.7	250
2	18.8		20.5	
6	14.7	700	13.4	130
10	14.0		10.6	
20	12.9	563	7.9	104

A2.3.2 Pelletising bagasse

All ligno-cellulosic materials such as timber, straw, paper and bagasse represent a valuable energy source, however display problems due to their large volume to weight ratio, making the handling, storage and transport not only difficult but also expensive (LAMNET 2001:1). Pelletising sugarcane bagasse is a way of improving the fuel handling, transportation, conversion and also allowing for storage for off-season utilisation (Erlich, Ohman et al. 2005:569). Traditionally, this problem is overcome by drying the biomass resource (up till approximately 18-19% moisture content) and

compressing it at very high pressure into fuel briquettes or pellet. This process takes place at an average temperature between 100 and 120 degrees Celsius with average production costs of around 590 – 890 ZAR/ton of pellets and produces pellets with a lower heating value (LHV) of around 15.9~17.5 MJ/kg (LAMNET 2001:1).

However, recent developments in pelletising have resulted in processes that do not require additional drying processes and can biomass resources up to 35% moisture content. The process operates under a temperature range of 55-60 degrees Celsius, which eliminates the need for cooling. The energy requirements of this process is around 70-100 Wh/kg of product depending on the initial moisture content (LAMNET 2001:2). The product characteristics are a moisture content of around 8-10%, a LHV of 16.7 – 18.5 MJ/kg and a density of 700 – 750 kg/m³ (LAMNET 2001:2). In comparison, the moisture content of commercially available bagasse pellets from Cuba and Brazil range from 4.6 – 6.6 wt% (Erlich, Bjornbom et al. 2006:1536). The operational costs of this new process are 296~493 ZAR/tonne of wet bagasse (LAMNET 2001).

The capital costs reported are as follows (LAMNET 2001:1):

- 1t/hour = 3,75 mRand
- 4t/hour = 6,42 mRand
- 5t/hour = 8,19 mRand.

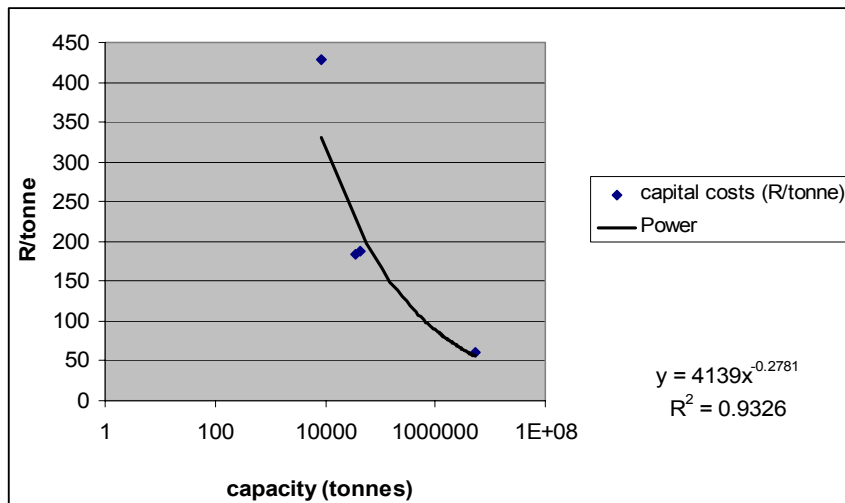


Figure A2- 1 Capital costs of pelletising technologies (logarithmic scale)

Some studies of pelletising sorghum bagasse are carried out by the European Biomass Industry Association (EUBIA). The capital costs for pelletising 5,2 mtonne of bagasse into 2,8 mtonne of pellets are 315 million ZAR, which is about 61 ZAR/tonne of wet bagasse (Grassi, Fjallstrom et al. 2002:1387). The yield is around 54%.

A2.3.3 Combustion of raw bagasse for electricity production

Bridgwater & Brammer (2002) provide operational and capital cost data for a combustion plants consisting of a fluid bed combustor and a Rankine steam cycle to convert the superheated steam into electricity. The capital costs for the fluid bed combustor are given by the following equation (Bridgwater, Toft et al. 2002:212):

$$TPC_{conv,comb} = 4747(E_{th})^{0.80} \quad (A2-1)$$

Whereby, $TPC_{conv,comb}$ is the total plant cost in kZAR and E_{th} is the energy in the prepared feedstock, MW_{th} LHV. The additional capital costs for the steam cycle are as follows:

$$TPC_{gen,steam} = 1147(E_{e,gross})^{0.695} \quad (A2-2)$$

Whereby, $TPC_{gen,steam}$ is in kZAR and $E_{e,gross}$ is the gross generator output.

The operational costs for the fluid bed combustor consist of internal power consumption (10~18 % over the total combustion and generation system), maintenance costs and labour costs. The maintenance costs of steam cycles are around 4% of installed capital costs or an equivalent of 0.2~0.4 ZAR/kWh. The labour costs decrease with size, because small scale systems require relatively more labour for reception, storage and handling of the feedstock. Around 0.12 persons per MWth of feedstock input are required for systems up to 50 MWth feedstock input, while larger systems (>100 MWth feedstock input) require 0.06 persons per MWth feedstock input (Bridgwater, Toft et al. 2002:213).

Data provided by Associated Energy Services (Pty) Ltd, based in South Africa, provided the capital and operational cost data displayed in table A2.5. for a fully automated biomass firing steam and power generation plant, capable of storing and transferring

biomass to point of use in a boiler, a high pressure watertube boiler, with superheater (with moving grate combustion system, fuel feeders and spreaders), water treatment facilities, air preheater, economiser and controls, a steam turbine with process steam passout facility, condensers, cooling tower, cooling water and condensate circulation pumps, controls and basic switchgear for delivery of power at 6.6 kV:

Table A2- 5 Operational and capital cost for steam combustion plant (Williams 2005)

MW capacity	Opex (ZAR/MWh)	Capex (mZAR)	Efficiency*
3	47.2	51.3	0.27
4.5	42.6	73.4	0.27
10	77.1	143.8	0.27
14	68.6	190.4	0.3
25	63.9	330.3	0.3
40	50.2	450.8	0.32
80	50.2	518.4	0.34
120	50.2	596.2	0.34
160	50.2	685.6	0.34

* The economies of scale in efficiencies are assumed

The efficiencies in this table are estimates. Botha & von Blottnitz (2006) used a 30% overall efficiency for the production of electricity from dry bagasse with an LHV of 16 MJ/kg (Botha and von Blottnitz 2006:2658).

Direct application of fluidized bed combustion (FBC) to raw bagasse with a 47-52 wt% moisture content is not possible, because bagasse alone cannot be fluidized due to its fibrous nature and low density (Rasul and Rudolph 2000:124). Therefore, it must be mixed with some other inert fluidizing solids, which causes on its turn segregation problem if the particle sizes of the inert material and the bagasse are not aligned (Rasul and Rudolph 2000:129). However, such problems are not reported in sugar mills in Mauritius, which have been cogenerating electricity and heat using boilers with conventional and condensing steam turbines since the late 1960s (Beeharry 1996:442).

In Nigaragua, a sugar mill was build with 7,000 ton/day crushing capacity installed 5 boilers and extraction-condensing turbines to burn bagasse and operate a power plant at 24 MW in the off-season; 330 days a year. However, additional air dried wood from nearby forest plantations would be required as additional feedstock. However, the project failed commercially, because the electricity price was too low (252 ZAR/MWh).

Instead, an electricity price of 527 ZAR/MWh was required to make it economically feasible (Riegelhaupt 2003:3).

Other case studies were reported in Honduras and Cuba. The following data was reported:

Table A2- 6 Cogeneration and Expanded Generation Profiles in Sugar Mills (Riegelhaupt 2003:4)

country	site	net generation		investment costs		direct operational costs
		MW	MWh/yr	ZAR	mZAR/MW	ZAR/MWh*
Honduras	Aysa	4.7	18945	409760	0.09	95~315
	Tres Valles	6.5	26035	10874400	1.67	95~331
	Azunosa	24.0	46871	37981600	1.58	63~165
	La Grecia	1.0	3600	1891200	1.89	n.a.
Cuba	FNTA 1	5.0	35330	20960800	4.19	229
	FNTA 2	15.0	55296	25373600	1.69	205
	30 Noviembre	11.0	86400	51220000	4.66	221
	A. Martinez	7.0	53700	31677600	4.52	221

* includes fuel procurement/transportation/preparation & operation and maintenance of plant

These plants ran in the off-season on fuel wood. The economic radius of transport of is 120 km (Riegelhaupt 2003:4). The major obstacles to undertake the production of electricity for the sugar mills to the national grid was on all cases the uncertainty about electricity prices and the difficulties in negotiating power purchase agreements in favorable terms (Riegelhaupt 2003:5).

A2.3.3.1 Comparison and results

The operational & capital costs are compared in the following graphs:

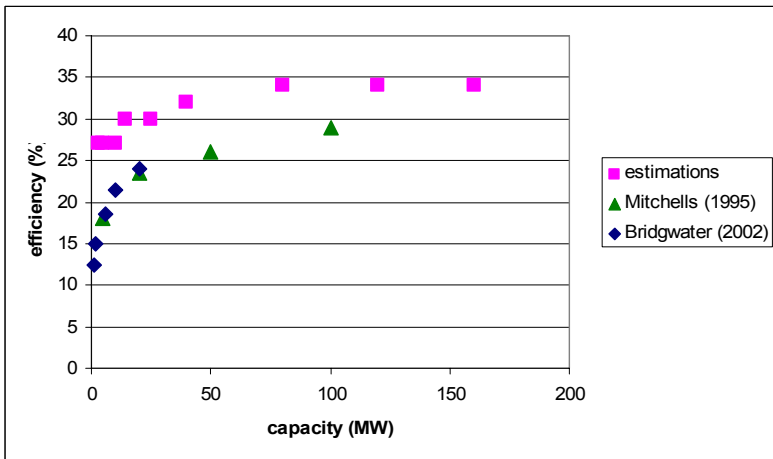
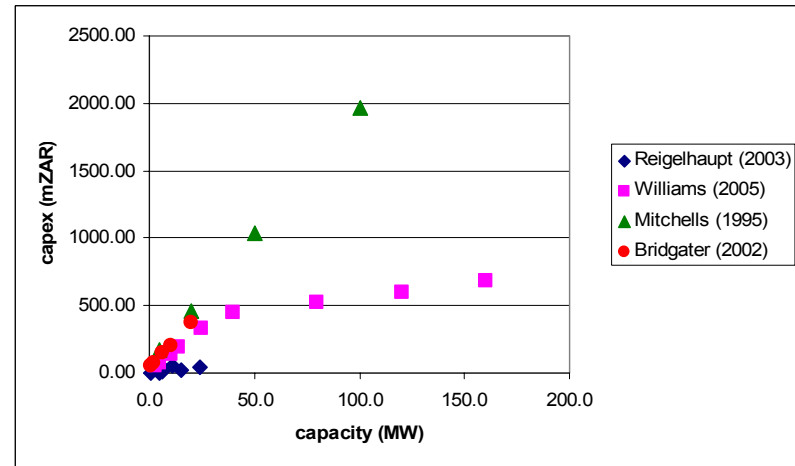
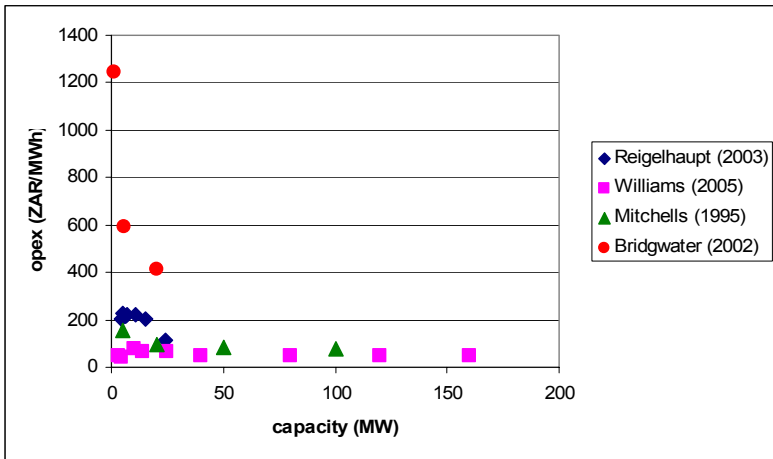


Figure A2- 2 Comparison of operational & capital costs and efficiencies of biomass combustion technologies

The figure show that in particular the operational costs for small-scale systems differ substantially for the four different literature sources. It is suggested to use the intermediate numbers of Reigelhaupt (2003) for small systems. The capital costs seem to correlate for small-scale system, however, differ substantially with regard to economies of scale. Williams (2005) numbers seem to be optimistic, so it is assumed that the intermediate numbers are used for larger scale systems. In terms of the efficiencies, the estimation seems to be too positive relative to Bridgwater (2002) and Mitchells (1995) findings. It is suggested to use Mitchells (1995) and Bridgwater (2002) numbers

A2.3.4 Combustion of pelletised bagasse

Bridgwater and Brammer (2002) report the following relationship between the conversion efficiency of fluid bed combustors (> 25 tonne/hr) and the feed moisture content (Bridgwater, Toft et al. 2002:211):

Table A2- 7 Conversion efficiency of fluid bed combustors depending on the moisture content of the feedstock (Bridgwater, Toft et al. 2002:211)

moisture content (%wt basis)	conversion efficiency (% LHV)
0	88
10	87.5
20	87
30	86.5
40	85
50	83

These data points suggest that the use of bagasse pellets with a moisture content of around 10% instead of raw bagasse (50 wt% moisture) will increase the combustor efficiencies with 4~5%.

In recent case studies, pellets have been used for the production of electricity in a small co-generation plant of 50 MW with 40% heat utilisation and operational costs of 394 ZAR/MWh. Using 270,000 tonnes of pellets, with a caloric value around 16.7~18.5 GJ/tonne will produce 335 GWh (Grassi, Fjallstrom et al. 2002:1388). The total electrical energy efficiency of these combustions plants is thus around 26~27%. In another case study, 1,4 tonnes of bagasse pellets are produced per day (LAMNET 2001). Using these pellets in a combustion chamber of a cogeneration plant, allows for a gross electric net

energy production of 800,000 KWh p.a. (which equates to an electrical efficiency of 33%) and a net thermal energy production of 1850000 KWh p.a. with a operating time of 8000 hr p.a.. The capital costs for the cogeneration plant would be around 950,000 ZAR (LAMNET 2001:3).

A2.3.5 Gasification of raw bagasse

Experimental work of De Filippis et al. suggests theoretical energy efficiencies⁷³ for gasification of undried bagasse (35 wt% moisture) of 0.79% (De Filippis, Borgianni et al. 2004:250). Bridgwater & Brammer (2002) estimate the following capital costs data for gasification plants with a feeding mechanism, the gasifier, gas cleaning systems and a tar cracker as (Bridgwater, Toft et al. 2002:219):

$$TPC_{conv,gas} = 412.8 \times (Q_{feed,dry} \times 1000)^{0.6983} \quad (A2-3)$$

With $TPC_{conv,gas}$ in kZAR and $Q_{feed,dry}$ in tonnes/hr. The costs of a gas-fired dual fuel diesel engine need to be added to estimate the total costs for a gasification plant. The capital costs for these engines is given by (Bridgwater, Toft et al. 2002:220):

$$TPC_{eng,gas} = 9949(P_{e,gross} \times 1.25)^{0.96} \quad (A2-4)$$

With $TPC_{eng,gas}$ in kZAR and $P_{e,gross}$ represent the gross generator output for a single engine in MW.

The operational costs for the gasification plant are given by labour requirements, internal power requirements (40 kWh/odt) and catalyst for the cracker (200 ZAR/odt)⁷⁴. The labour costs for the gasifier depend on the total input flow of feedstock as follows (Bridgwater, Toft et al. 2002:204):

$$Labour = 1.04 \times (Q_{feed,dry})^{0.475} \quad (A2-5)$$

⁷³ Energy efficiency is defined as the ratio between the actual heat content of the syngas and the potential higher heating value of the bagasse feedstock.

⁷⁴ Based upon a dolomite price of 296 ZAR/tonne.

where labour is the number of people required to handle stream and $Q_{\text{feed,dry}}$ is the feed in odt/hr. The labour requirements for the engine are as follows (Bridgwater, Toft et al. 2002:209):

$$\text{Labour}_{\text{totaleng}} = 0.4847(P_{e,\text{net}})0.483 \quad (\text{A2-6})$$

In A2 - 6, $P_{e,\text{net}}$ is the total gross electricity output minus the internal power requirements (3%).

An alternative for this system is the use of BIG/GT-CC (biomass intergrated gasifier/gas turbine-combined cycle). Such system would not require a tar cracker and uses a gas turbine combined cycle with a min. efficiency of 30%; 40% with a gas turbine input of 20 MWth up to 53% with inputs higher than 100 MWth (Bridgwater, Toft et al. 2002:224).

The capital costs for such system can be described as follows (Bridgwater, Toft et al. 2002:205):

$$\text{TPC}_{\text{gen,gfcc}} = 21289 \times (P_{e,\text{gross}})^{0.85} \quad (\text{A2-7})$$

With $\text{TPC}_{\text{gen,gfcc}}$ in kZAR and $P_{e,\text{gross}}$ as gross power output in MW. In terms of operational costs, an average of 3% of the gross power output is used internally, maintenance costs of around 0.09 ZAR/kWh and labour requirements 25% higher than estimates for the steam cycle (Bridgwater, Toft et al. 2002:226). Operational costs of BIG/GT-CC estimated at 300 ZAR/MWh are lower than conventional combustion technology (rankine cycle) with operating costs of 630 ZAR/MWh (Gomez, Augusto Barbosa Cortez et al. 1999:206). Other sources suggest that the capex for a gasification plant can be assumed to be 85% of equivalent steam plant costs (European Commission 2005). Operational expenditure for a gasification plant can be assumed to be 133% of those of a steam plant. On the basis of data provided by Associated Energy Services (Pty) Ltd, the following data in terms of capital and operational costs are therefore derived:

Table A2- 8 Capital and operational costs for gasification technologies derived from (Williams 2005)

MW capacity	Opex (ZAR/MWh)	Capex (mZAR)	Efficiency*
3	62.8	43.6	0.33
4.5	56.7	62.4	0.33
10	102.5	122.2	0.33
14	91.2	161.9	0.36
25	85.0	280.8	0.36
40	66.8	383.2	0.38
80	66.8	440.6	0.4
120	66.8	506.7	0.4
160	66.8	582.7	0.4

* The economies of scale in efficiencies are assumed

A2.3.5.1 Comparison and results

On the basis of this information, the following comparisons can be made:

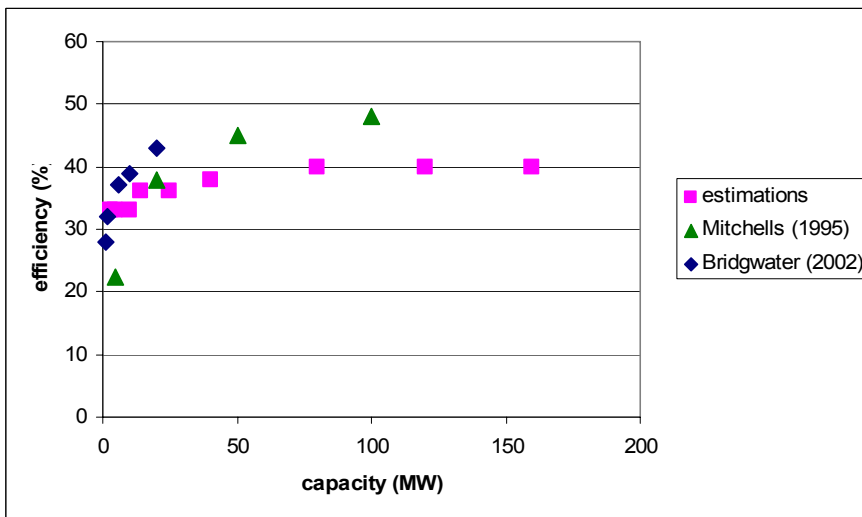
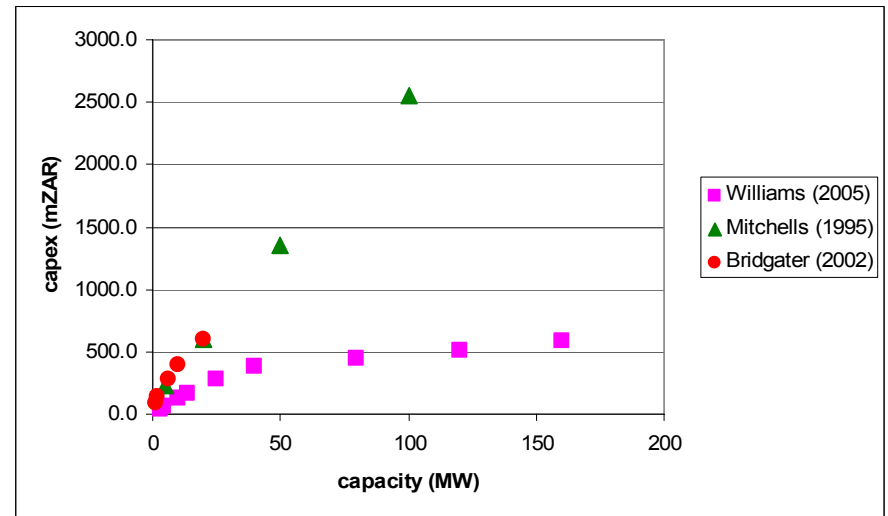
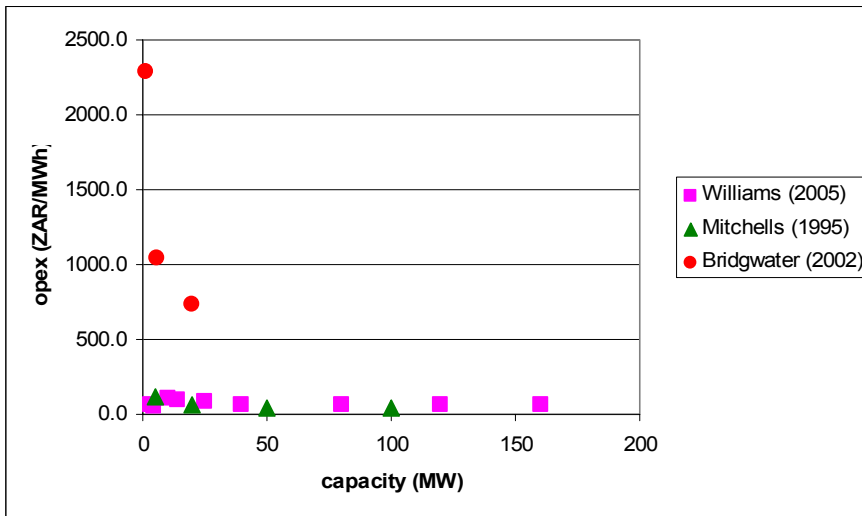


Figure A2- 3 Comparison of operational and capital costs and efficiencies of gasification combined cycle technologies

On the basis of this data, the gasification combined cycle technology (IGCC) seems to have more potential than a gasification plant combined with a fuel engine, especially because the technology is also developed for coal (EPA, 2006). As is the case for combustion technologies, there seems to be disagreement about the operational costs for small-scale technologies.

Furthermore, some sources suggest that the operational costs are higher than combustion (Bridgwater, Toft et al. 2002; European Commission 2005), while previous reports suggested it is lower (Mitchell, Bridgwater et al. 1995). Furthermore, there is disagreement about the capital costs. The EU data suggests that capital costs are lower than combustion technologies, while Mitchell et al. (1995) and Bridgwater et al. (2002) suggest it is higher. However, because gasification is a much more complex technology than combustion, it seems fair to assume that capital costs have to be higher and therefore the numbers of Bridgwater (2002) and Mitchell (1995) should be used. In terms of operational costs, the extra complexity should result in higher operational costs (especially in labour), although Mitchell et al. (1995) and Gomez et al. (1999) report lower operational costs. Bridgwater (2002) assumes additional labour costs of around 25%, which seems to be a reasonable assumption and should be followed within this report. In terms of efficiency, the numbers of Mitchells (1995) and Bridgwater (2002) correlate very well and should be used instead of the lower numbers of our own estimations.

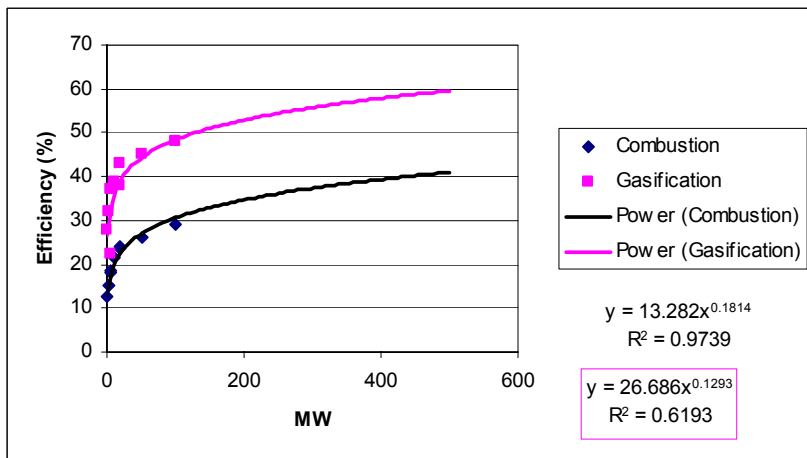
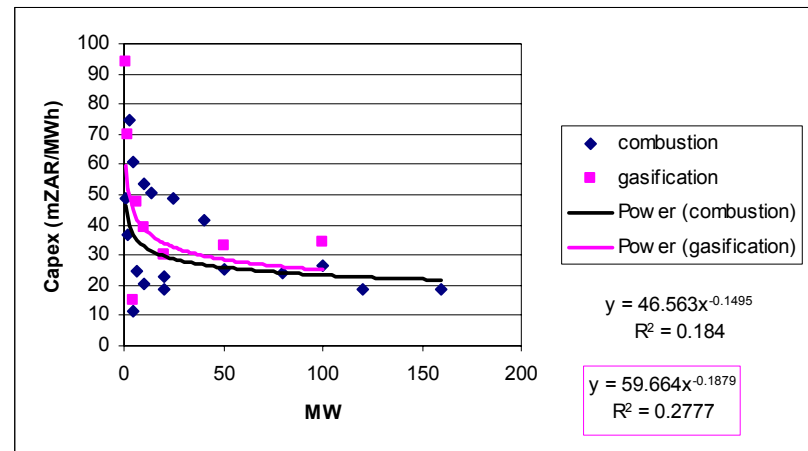
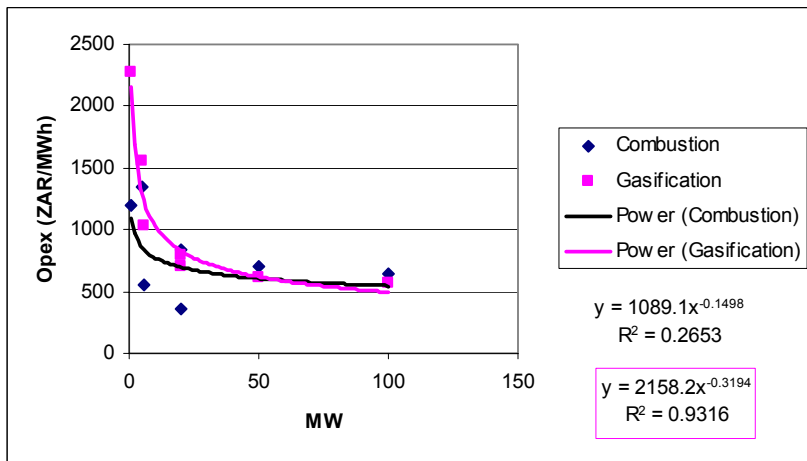


Figure A2- 4 Overview and curve fitting for efficiencies, operational and capital cost for combustion and gasification technologies for bagasse

The fitted curves are based on costs and efficiencies obtained from Mitchells (1995) and Bridgwater (2002). The costs of raw materials were subtracted from the stated production costs as these will be calculated separately in our models. It has to be noted that the costs found varied extremely, especially in the lower capacity ranges: Values ranged from a few ZAR/MW (Gomez, Augusto Barbosa Cortez et al. 1999:198) to a few thousand (Bridgwater, Toft et al. 2002:232) in the case of capital costs. The latter's values were chosen to keep the analysis conservative, rather than overly optimistic.

A2.3.6 Gasification of pelletised bagasse

Decreasing the moisture content of bagasse by drying or conversion into bagasse pellets has positive impacts on the gasification process. In experiments by Gomez et al. bagasse was dried up to 9.85 and 10.23 wt% with higher heating values of 18,95 and 18,85 Mj/kg, respectively. However, the major advantage of bagasse pellets is that they did not result in feeding difficulties, such as clogging and bridging, as was the case for bagasse (Gomez, Augusto Barbosa Cortez et al. 1999:213).

Especially in small-scale gasifiers (< 5MW), a reduced moisture content of the feedstock has a positive impact on the system performance (Brammer and Bridgwater 2002:272). Brammer studied the effects of feedstock drying on the economics of a biomass gasifier-engine with external thermal and catalytic tar cracking reactors, gas clean-up and spark-ignition engine (Brammer and Bridgwater 2002:272). Capital costs for small scale gasifiers can be obtained by a correlation by Bridgwater:

$$C_g = 112,912m_B^{0.698}, \quad (A2-8)$$

Where m_B is biomass dry feed rate (kg/s) and C_g is in kZAR.

The lowest operational costs, 855 ZAR/MWh, were obtained from a system operating at a feed rate of 2.0 dt/h with a biomass cost of 296 ZAR/dt and incorporating a rotary dryer with burner drying from an initial moisture content of 50% to a final moisture content of 10% (Brammer and Bridgwater 2002:281). The total capital costs for this configuration are:

- dryer up to 10 wt% moisture content (8,2 mZAR)

- dryer up to 35 wt% moisture content (7,3 mZAR)
- gasifier (35,7 mZAR)
- IC engine (17,2 mZAR)
- Heat recovery (2,8 mZAR)
- Balance of plant (6,6 mZAR) (Brammer and Bridgwater 2002:277).

The overall electrical efficiency of these gasifier-engine CHP systems (Turn, Jenkins et al. 2002) is around 80% (Brammer and Bridgwater 2002:277).

Gomez et al. proposed a fluidized-bed air gasifier for the production of electricity from bagasse pellets. The design is modular with a thermal capacity of 280 KWh producing 252.68 Nm³/h of gas with an energy conversion efficiency of 60% (Gomez, Augusto Barbosa Cortez et al. 1999:208). Experimental work of De Filippis et al. suggest theoretical energy efficiencies for gasification of dried bagasse (8 wt% moisture) of 0.83% (De Filippis, Borgianni et al. 2004:240).

A2.3.7 Co-firing of raw or pelletised bagasse

Bagasse can be cofired with coal or fuel oil. Only limited tests are available in the public domain about co-firing of either raw or pelletised bagasse. Turn et al. (2002) conducted comparable tests with coal and fuel oil (83% and 17%), with coal, fuel oil and bagasse (25%, 13% and 62%) and with coal, fuel oil, bagasse and cane fibre (33%, 17%, 45% and 5%). These tests show that coal cofired with a high ratio of bagasse or cane fibre has a much lower boiler HHV efficiency, from 82 to 54%. However, steam pressure, steam output and steam temperature are comparable (Turn, Jenkins et al. 2002).

The coal-fired power station has a capacity of around 3 GW, which means that bagasse will only be a small percentage of the feedstock. Therefore, no penalties exist in terms of boiler efficiency.

Specific capital and operational costs of cofiring bagasse are unknown. Black & Veith (2005) suggest capital costs for cofiring biomass around USD 100 – 800 per Kw and operational costs of USD 7 – 26 per KW per year (Black & Veitch 2005:4-6). The following data are assumed on the basis of the operational costs of producing coal.

Table A2- 9 Operational and capital costs of co-firing bagasse in coal-fired power station

Operational and capital cost of co-firing bagasse in coal-fired power station

Efficiency of cofiring	0.33	GJ power/GJ
Conversion	277.78	kWh/GJ
Opex	150	ZAR/MWh
Capex	100	ZAR/t bagasse
Capex	0.83	mZAR/MW

The use of either pelletised or raw bagasse does not impose any penalties on the efficiency of co-firing (as is the case for combustion or gasification). The reason for this is that bagasse will be limited to max 5% of the total feedstock of the process. However, the major difference of raw versus pelletised bagasse is the operation time. Pelletised bagasse can be stored and therefore used throughout the year, while raw bagasse can only be used in those months that the bagasse is available (typically 6480 hours/year).

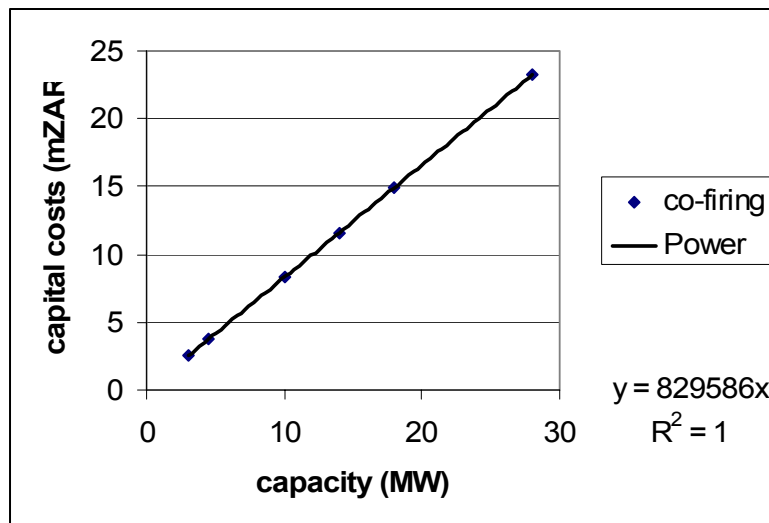


Figure A2- 5 Capital costs for co-firing of bagasse in existing coal-fired power plant

A2.3.8 Physiochemical production of bioethanol from bagasse

The non-enzyme based approach for the production of bioethanol from bagasse, acid is used for both the hemicellulose and cellulose hydrolysis. Fermentation takes place separately from the hydrolysis. A simplified flowsheet is presented in figure A2-6.

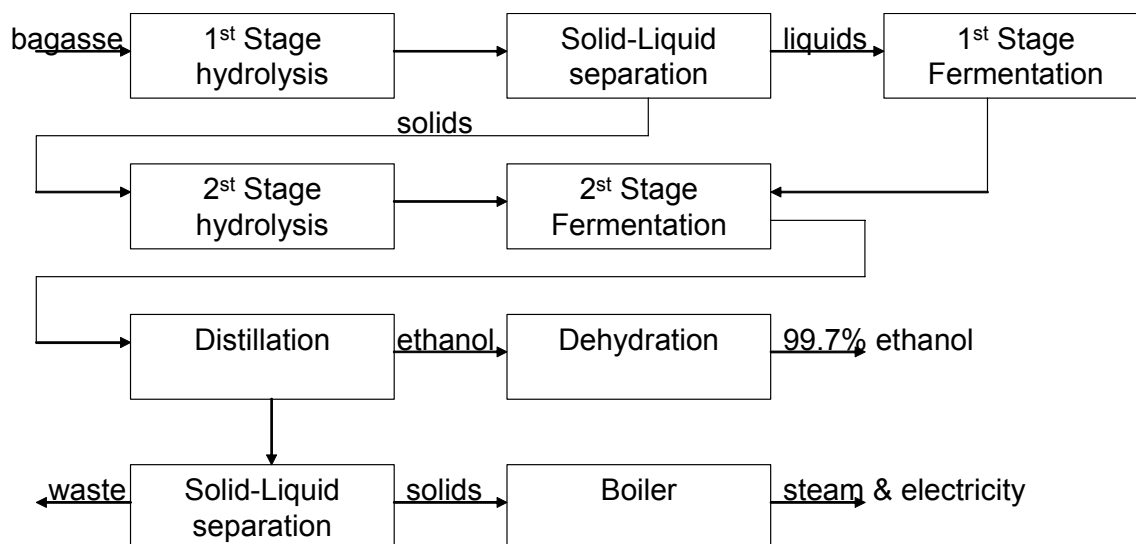


Figure A2- 6 Two-stage dilute-acid process flow diagram (Kadam 2000:28)

Hydrolysis takes place in a dilute sulfuric acid environment, while the fermentation of the six-carbon and five-carbon sugars is achieved by recombinant *Z.mobilis* (Kadam 2000:29). The ligneous residue after distillation can be used to produce electricity and steam. The electrical efficiency of the co-generator is around 9.8 %. The process has the following characteristics on the basis of the production of 1 litre 99.7% ethanol:

Table A2- 10 Input-output for production of 1 litre bioethanol in two-stage dilute acid process (Kadam 2000:230)

Production of 1 litre bio-ethanol in two-stage dilute acid process			
input	bagasse	(kg)	4.24
	water	(kg)	15.23
	diesel	(kg)	0.02
output	ethanol	(l)	1
	CO ₂	(kg)	5.55
	biogas methane	(kg)	0.07
	net electricity	(MJ)	4.83

The total yield of the process described is 186 kg of bioethanol per tonne of bagasse (34 wt% moisture) (Botha and von Blottnitz 2006:2658).

Pyrolysis is one of a number of alternatives to transform biomass into liquids. Conventional pyrolysis has been used to thermally decompose the organic components of biomass into charcoal, while pyrolysis with short residence times (called fast, flash,

rapid or ultrapyrolysis) at moderate temperatures is used to produce liquid products (Yadan 2004:654). In a vacuum pyrolysis experiment of a sugarcane bagasse sample of 20 kg (air-dried with a 8 wt% moisture content) obtained liquid yields up to 31%, while 22% gasses were produced (Garcia-Perez, Chaala et al. 2002:118). The bio-oil obtained had a gross calorific value of 22.4 MJ/kg, a moisture content of 13.8% and an ash content of 0.05 wt%. These characteristics meet the requirements for use in gas turbine fuels (Garcia-Perez, Chaala et al. 2002:121). Bridgwater (2002) examined the development of a fast pyrolysis plant together with either gasification or combustion technologies. The total plant costs for a fast pyrolysis plant can be described by the following equation (Bridgwater, Toft et al. 2002:203):

$$TPC_{pyr} = 402.7*(Q_{dry} * 1000)^{0.6194} \quad (A2-9)$$

In (2), TPC_{pyr} is in kZAR and Q_{dry} is the biomass dry feed rate (tonnes/hr).

In order to allow for disruptions during the pyrolysis plant operations, pyrolysis liquids can be stored. The total plant costs of pyrolysis liquid storage can be estimated using the following equation (Bridgwater, Toft et al. 2002:203):

$$TPC_{store} = 1174.5*(Q_{liq})^{0.4045} \quad (A2-10)$$

In A2 – 10, TPC_{store} is in kZAR and Q_{liq} is the output flow of the pyrolysis liquid in tonnes/hr. With typical densities of bioethanol of 790 kg/m³ and bioliquids around 875 kg/m³ (Scurlock 2006), this implies that the capital costs per m³/day are around 295000 – 307000 ZAR.

In terms of operational cost, there are the costs for internal energy consumption (40 kWh/odt) and labour costs. Labour costs for the gasifier depend on the total input flow of feedstock as follows (Bridgwater, Toft et al. 2002:204):

$$\text{Labour} = 1.04x(Q_{feed,dry})^{0.475} \quad (A2-11)$$

where labour is the number of people required to handle stream and $Q_{feed,dry}$ is the feed in odt/hr.

The capital and operational costs and curve fitting exercise to the data is displayed in the figures below:

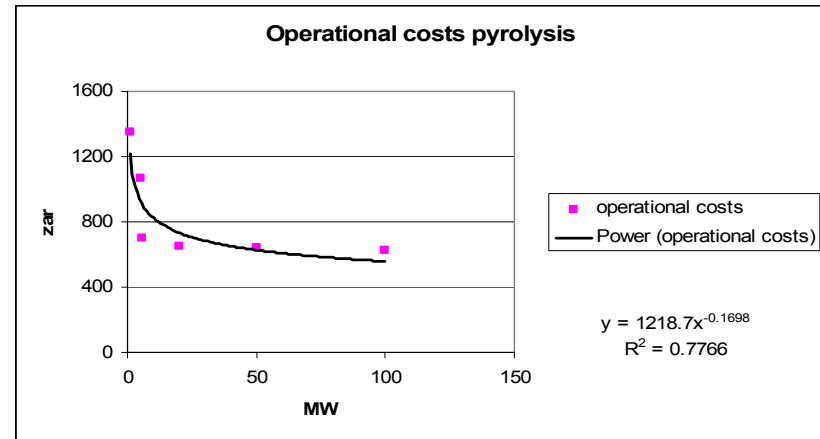
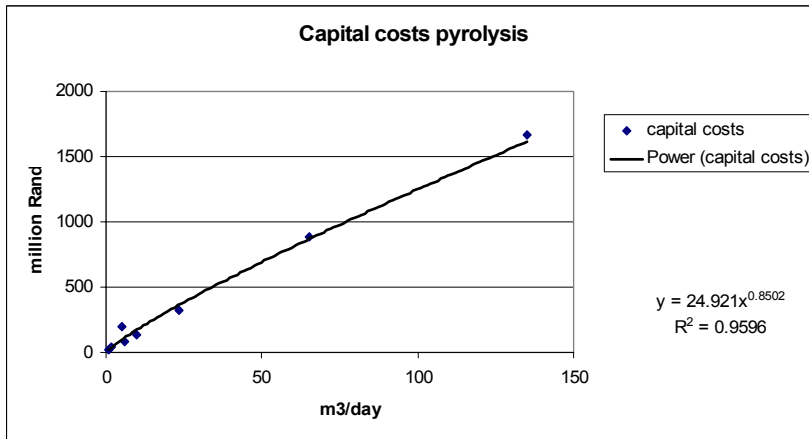
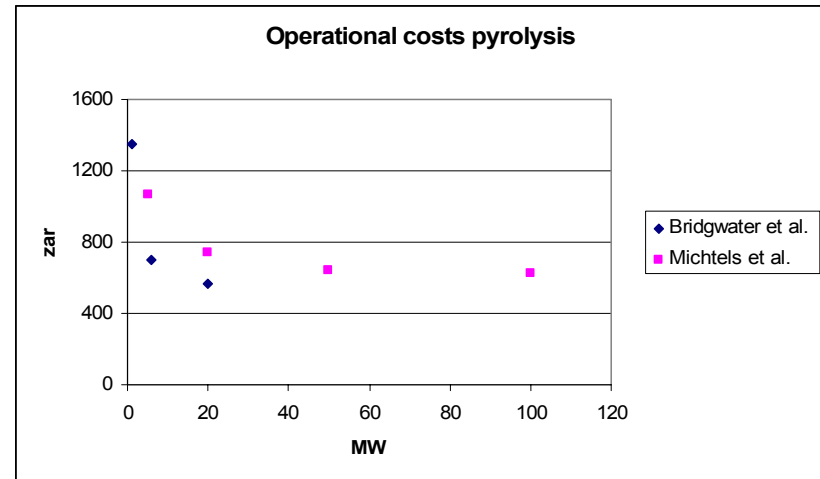
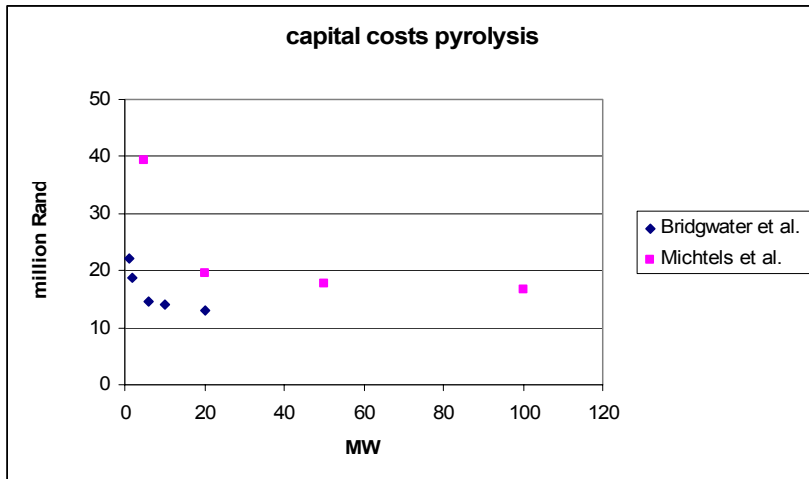


Figure A2- 7 Operational and capital costs for pyrolysis

The efficiency of pyrolysis is scale-dependent. The following figure gives an estimation of the efficiency of pyrolysis on the basis of information from Mitchell et al. (1995) and Bridgwater et al. (2002):

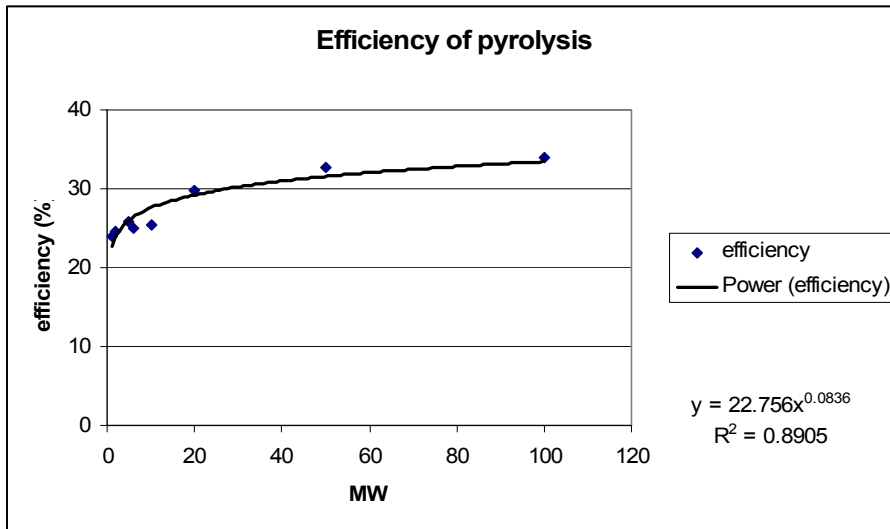


Figure A2- 8 Efficiency of pyrolysis

Another way of physiochemical production of fuels from bagasse is CO₂ synthesis into biomethanol. Sugarcane bagasse pellets can be used as feedstock and energy source for this process. The process is schematically described in figure A2.9.:

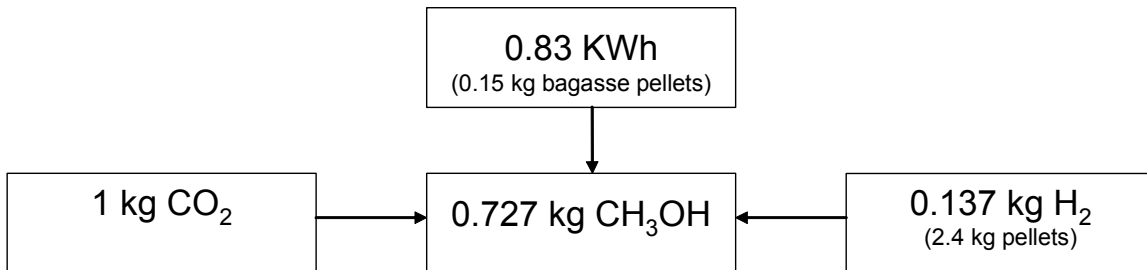


Figure A2- 9 Methanol production by CO₂ hydrogenation (Grassi, Fjallstrom et al. 2002:1388)

Any cost data for this process has not been obtained and this option shall therefore not be included into the overall analysis.

A2.3.9 Biological production of bioethanol from bagasse

An enzymatic approach is used in the biological production of bioethanol from bagasse. The hemicellulose portion in bagasse is hydrolysed by dilute-acid pretreatment. Subsequently, the cellulose and hydrolysed hemi-cellulose is simultaneously hydrolysed and fermented by synergistic action of cellulase and B-glucosidase enzymes (Kadam 2000:25). The required cellulase is produced by *T. reesei* using a treated slipstream (to remove toxic acids and organic species for the *T. reesei*) of the pretreated bagasse as a carbon source (Kadam 2000:27). The advantage of this system is that both inhibition effects of sugar products on the fermentation can be eliminated and both processes can run at their optimum temperature (Castillo 1992:426). A comparative study of Blanco (1982) of two alternative designs, stepwise saccharification-fermentation and simultaneous saccharification-fermentation⁷⁵, showed that the coupled system has higher yields of 0.20 kg Ethanol/ kg Bagasse than the alternative designs (0.18 and 0.1 respectively) after 40 hours (Blanco, Gamarra et al. 1982:663). These yield numbers are comparable to two stage dilute-acid process and the enzymatic process described previously by Kadam (2000) with yields of 0.186 and 0.238, respectively. The ligneous residue after distillation can be used to produce electricity and steam. The electrical efficiency of the co-generator is around 9.0 %. A simplified flowsheet diagram of the process is given in the next figure:

⁷⁵ In stepwise saccharification-fermentation all stages are separated, while simultaneous saccharification-fermentation combines enzymatic hydrolysis of cellulose with simultaneous fermentation of the sugars obtained to ethanol Grassi, G. (2001). "Microdistillery for Decentralised Bioethanol Production." Retrieved november, 2006.p. 371

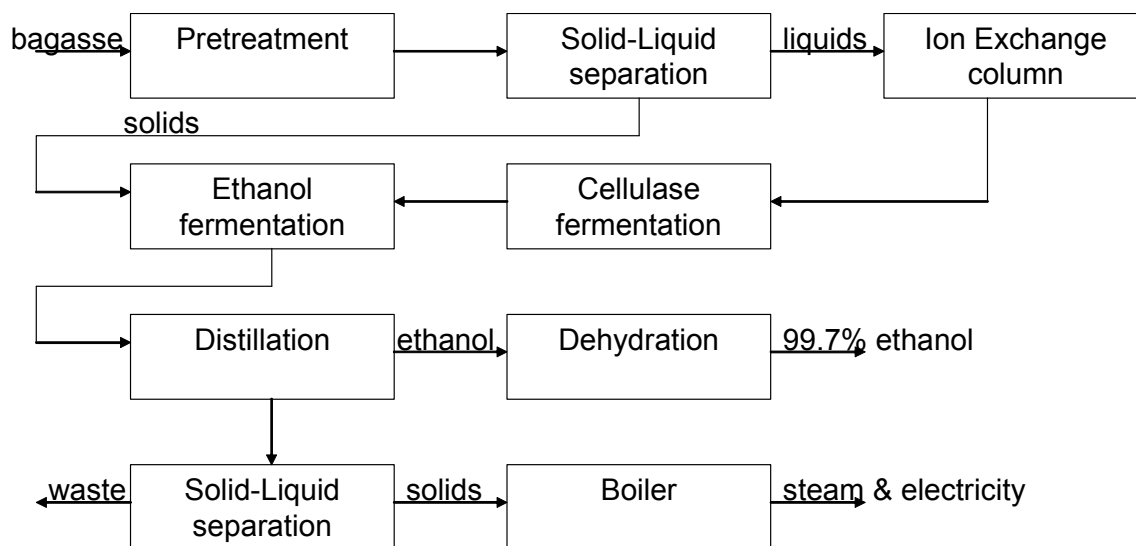


Figure A2- 10 Enzymatic process flow diagram (Kadam 2000:26)

The process characteristics on the basis of 1 litre 99.7% bioethanol are displayed in the next table:

Table A2- 11 Process characteristics of the enzymatic production of bioethanol (Kadam 2000:30)

Production of 1 litre bio-ethanol in enzymatic process			
input	bagasse (34 w% moi.)	(kg)	3.32
	water	(kg)	6.52
	diesel	(kg)	0.02
output	ethanol	(l)	1
	ligneous residue*	(kg)	1.47
	CO ₂	(kg)	3.88
	biogas methane	(kg)	0.05
	net electricity	(MJ)	2.85

* average heating value of residue is 21.54 MJ/kg

On the basis of enzymatically hydrolysed sugarcand bagasse system processing 217 tonnes/day of raw bagasse (18 wt% moisture), an economic assessment for the production of 95% (v/v) was carried out. The following data was reported:

Table A2- 12 Estimated costs for a plant producing 37 m³ of 95% (v/v) ethanol/day from bagasse in a bioconversion integrated system (Castillo 1992:426)

unit	operational costs (ZAR/m ³ ethanol)	unit	yield	total costs (ZAR)
raw material	426	pretreatment	0.82 (kgB/kgB)	40582000
labour	79	coupled system	0.13 (kgE/kgB)	67768000
chemicals	378	enzyme production	4.5E8 (U/day)	70998800
utilities	764	distillation	37.2 (m ³ /day)	20409200
depreciation	1718	enzyme recovery	8.8E7 (u/day)	15050800
maintenance	118			
plant overheads	173			
administration	118			
by-product credit	-260			
total	3514	total		215124000

There has been quite some progress in reducing the production costs of ethanol from cellulosic feedstock; from 8.35 ZAR/litre in 1980 to 3.7 ZAR/litre around 1995.

Projections for the production costs are as low as 1.65 ZAR/litre if cellulytic enzymes are recirculated and by-products are utilised (Szczodrak and Fiedurek 1996:370).

Furthermore, recent large scale investments (~315 million ZAR) by the US government in the development of enzymes to break down lignocellulose into sugars have led to a thirty-fold decrease in the costs of enzyme technology. Current estimates (2006) are in the range of 0.63 ZAR/litre of enzymes (Bell and Attfield 2006:4).

In 1983, a techno-economic evaluation of a bioethanol plant from cellulosic feedstock was carried out by Gulf Oil. On the basis of 2000 tonne of cellulose waste per day about 567,750 litre of ethanol would be produced. The capital costs would be around 94 million ZAR and an end product sale price of 2 ZAR/litre (Mitchell, Bridgwater et al. 1995:372).

In 2004, an economic evaluation took place of the co-production of cellulosic bioethanol, power and heat. The cellulosic material is converted into fermentable sugars by mild alkaline extraction at low temperature and weak acid hydrolysis in pressurized hot water. The sugars are fermented to produce bioethanol, while the non-fermentable organics are used to produce heat and electricity in a CHP (Reith, den Uil et al. 2003:1).

The production of 156 kton bioethanol (99.9 vol%) can be produced at an energetic efficiency of 40-55% (net energy output of ethanol); the internal steam and electricity

consumption are fully covered by CHP of non-fermentable biomass fractions. Furthermore, a surplus electricity can be supplied to the grid with an energy efficiency of 15% (LHV). The capital and operational costs for this plant are given in the following table:

Table A2- 13 Economic evaluation for a 156 kton/year bioethanol plant with CHP (Reith, den Uil et al. 2003:1)

feedstock costs		ZAR/odt	197~790
total investment		mZAR	2322~3092
O&M costs	feedstock costs	mZAR/yr	128~385
	cellulase*	mZAR/yr	583~1008
	others**	mZAR/yr	109~188
	total	mZAR/yr	1067~1324
ethanol production costs	feedstock	ZAR/l	0.59~1.88
	cellulase	ZAR/l	2.96~5.04
	others	ZAR/l	0.59~0.89
	capital	ZAR/l	2.77~3.66
	gross ethanol price	ZAR/l	8.10~10.67
	electricity***	ZAR/l	-1.09
	net ethanol cost	ZAR/l	9.09~9.78

* cellulase costs is 59000 ZAR/tonne of enzyme

** others include Ca(OH)₂, ash disposal, maintenance, labour

*** surplus electricity revenue is 0.5 ZAR/kWh

In terms of capital costs, logen Corporation is teaming up with Royal Dutch Shell to construct a cellulosic ethanol demonstration plant using enzymes to convert the cellulosic material into ethanol. The capital costs are around 2758 mZAR for a 182 million litre annual production capacity plant (Collins 2006:5). In general, the capital costs per litre of cellulosic ethanol is 5 to 6 times higher than corn ethanol mounting up to 7.4~9.4 ZAR/litre of bioethanol (Collins 2006:13). The yield is about 318 litre of ethanol per tonne of cellulosic material and the costs of enzymes per litre of cellulosic ethanol is estimated at 52~86 ctZAR (Collins 2006:6).

A2.3.9.1. Comparison and results

The following figures compare operational and capital cost for the different plants:

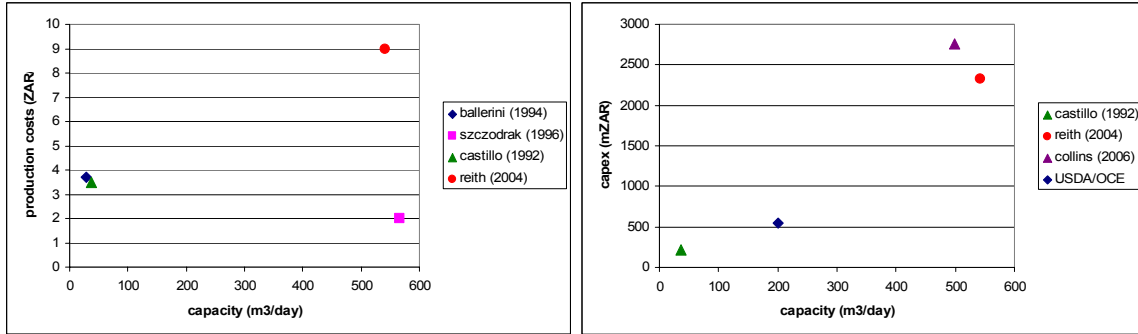


Figure A2- 11 Comparison of operational and capital costs of enzymatic hydrolysis of sugarcane bagasse

The estimates for the production costs of bioethanol are quite spread; although the discussed systems are all enzymatic hydrolysis of cellulose. Szczodrak (1996) reports future projects for the production costs as low as 1.65 ZAR/litre if cellulytic enzymes are recirculated and by-products are utilized, however, those number seem still to be very optimistic. It is suggested here that intermediate numbers should be used, which would be around 4 ZAR/litre of bioethanol.

The capital costs seem to fit a power function with limited economies of scale can be detected within the numbers reported (see figure A2-12). This can be due to the fact that it is still a new technology and commercial plants have yet to be built.

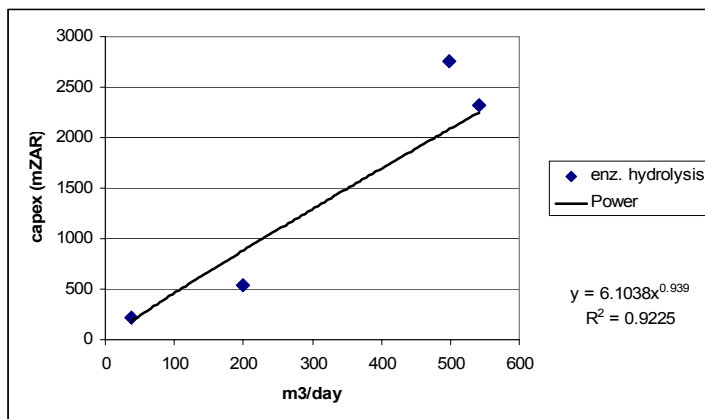


Figure A2- 12 Power function fitting the capital costs of enzymatic hydrolysis

A2.3.10 Decentralised production of electricity from bioethanol or pyrolysis fuels

Bridgwater & Brammer (2002) provide details liquid-fired dual fuel engine models, which can be used to produce electricity from liquid energy sources decentralised. These engines can be build in modules of 5, 7,5 and 10 MW with a total upper limit of 40 MW in capacity. The gross electrical efficiency of these engines is given by the following equation (Bridgwater, Toft et al. 2002:207):

$$N_{elec} = -0.002329 (E_{fuel})^2 + 0.313 (E_{fuel}) + 38.6 \quad (A2-12)$$

In A2 – 12, N_{elec} is the gross electrical efficiency, % LHV basis and E_{fuel} is the energy supplied by the energy source, MW_{th} LHV basis. If the energy fuel is a mixture, the energy supplied by the mixture should be used within this formula. The capital costs (including day storage for the fuel, lower viscosity and and fuel pre-heating) per engine is given by the following equation (Bridgwater, Toft et al. 2002:208):

$$TPC_{engine} = [821(P_{e,gross})^{0.954}] \times 10.9 \quad (A2-13)$$

In (5), TPC is in kZAR and $P_{e,gross}$ is gross generator output in MW. If they are build in stacks, the total capital costs for the unit decrease as follows (Bridgwater, Toft et al. 2002:208):

$$TPC_{totaleng} = TPC_{eng} \times n^{0.9} \quad (A2-14)$$

In A2 – 14, n is the number of engines used. The operational costs consist of the costs for additional fuel required (methanol or diesel oil), the labour costs, maintenance costs incl. lubricants (0.10 R/kWh) and internal power consumption (-3%). The labour requirements are as follows (Bridgwater, Toft et al. 2002:209):

$$Labour_{totaleng} = 0.4847(P_{e,net})^{0.483} \quad (A2-15)$$

In A2 – 15, $P_{e,net}$ is the total gross electricity output minus the internal power requirements (3%).

Using data on fuel engines provided in the introduction, the following two graphs show the trendlines for both capital and operational costs

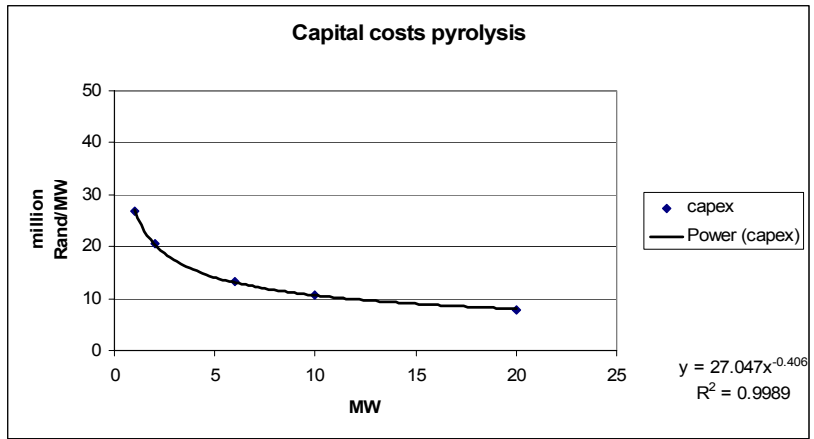


Figure A2- 13 Capital costs for a fuel engine

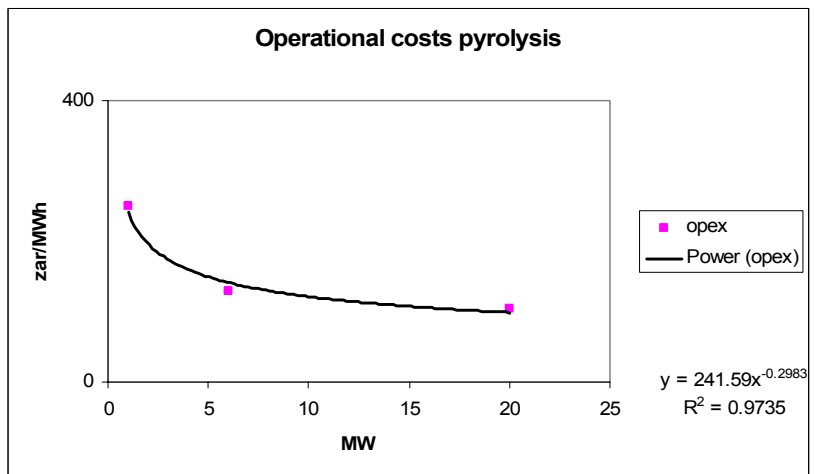


Figure A2- 14 Operational costs for a fuel engine

Because of the small-scale application of the fuel engines, there are no economies of scale. The efficiency of the fuel engines using a pyrolysis-produced biofuel with a caloric value of 22.4 MJ/kg is thus equal to 41%.

A2.3.11 Gelfuel production

The production of gel fuel from bioethanol is a relative new technology, which has been promoted by Worldbank projects since 2000. The capital and operation cost data as well

as the efficiency of the process are described by Utria (2004). The following functions are derived:

$$OC_{gel} = 4.7 \quad (A2-16)$$

$$CC_{gel} = 3.85 * C_{gel} \quad (A2-17)$$

$$EF_{gel} = 1.2 \quad (A2-18)$$

Operational costs (OC_{gel}) are in ZAR/liter of gelfuel produced, capital costs (CC_{gel}) in ZAR, the efficiency (EF_{gel}) is in liters of gelfuel per liter of bioethanol; and the capacity (C_{gel}) of the gelfuel installation is in liters per year.

A2.3.12 Grid connections

The grid connection costs is the costs associated with connecting large-scale generating capacities to the grid (so not household connections, which associated costs are discussed in appendix A1 and in A2.3.13). The costs for grid connections are highly affected by local conditions, such as location of the plant, the size of the plant and the grid voltage at the connection. However, the costs are relative small with respect to the total costs for the generation systems and can be estimated as follows (Bridgwater, Toft et al. 2002:210):

$$TPC_{grid} = 2783x(P_{e,net})^{0.537} \quad (A2-19)$$

Where, TPC_{grid} is the total cost for grid connection in kZAR and $P_{e,net}$ the power supplied to the grid in MW.

A2.3.13 Rural electrification (from grid and non-grid)

Rural electrification is essential for the social and economic developments in rural areas by stimulating local industrialisation, agricultural production, social services and education. However, Ranagathan (1992) concluded that rural electrification in many African countries is not financially viable, especially because of the very limited productive use of electricity (Statistics SA 2005:29). More recently, this conclusion was confirmed by Gaunt (2005) who suggest that rural electrification is not viable according to traditional economic assessments methods. Instead, a shift should be made towards the use of social objectives to evaluate rural electrification (Gaunt 2005:1309).

Currently, there are only two off-grid projects in South Africa: a 11 kW generation system in the Eastern Cape on the basis of wind energy and a 86 kW hybrid system containing wind- and solar energy 10 km further (Ruffini 2006:37).

Typical costs for the supply of electricity in rural areas (with an area load density of < 50 kW/km² and a consumer density of < 75 consumers/km²) are:

- grid based: 950 – 4000 R/MWh
- non-grid based: 2000 – 8000 R/MWh (Scurlock 2006:45).

Mason (1990) determined the average total economic costs of rural electricity supply including the capital costs of distribution, the long run marginal costs of energy supplied to the distribution grid, the operation and maintenance costs in developing countries to be 2000 ZAR/MWh (Zomers 2001:59). Without the costs of electricity generation, the number decreases to around 1500 ZAR/MWh (Zomers 2001:63).

The investment costs for rural electrification highly depend on the number of connections. Specific costs for South Africa (on the basis of 450 potential connections) are around 7000 ZAR/connection for non-grid are reported by Zomers (2001:60). However, this number includes the costs for installing PV panels. The cost for the distribution net itself should therefore be far less. Dale et al. (2004) mention distribution costs of around 395 ZAR/kW for the UK (Dale, Milborrow et al. 2004:1953). With an average household density in KwaZulu-Natal of 14 households/km² and an average energy consumption of 7.84 MWh/household.year (Statistics SA 2005), this would imply that the connections costs would be around 6530 R/km² or 467 R/connection. In terms of rural electrification by grid, Gaunt (2004) reports values from 3568 R/connection in 1995 to 2622 R/connection in 2001 (Gaunt 2005:1312). These costs are on the basis of low capacity, low cost grid connections instead of conventional grid connections. The costs for establishing an off-grid distribution network are thus considerably lower than distributing electricity from the grid. However, this does not take into account the costs for decentralised power production as discussed in paragraph A2.3.10.

More local figures on grid and non-grid connections and their subsequent subsidies can be found in appendix A1.

A2.3.14 Road and rail transport for bagasse and bioethanol

Basson (2004) reports road transport costs of 0.22 R/ton.km in South Africa (Basson 2004). Other sources, interviewed in 2006, report 0.36 to 0.67 R/tonne.km for road transport of coal in South Africa. European transport costs are around 1.3 R/tonne.km and are thus considerably higher. However, the costs for bagasse will be higher because of the density of sugarcane bagasse, which can be as low as 0.15 ton/m³ (Bridgwater, Toft et al. 2002), although other sources report a bulk density of around 50~75 kg/m³ (Scurlock 2006). Energy use of road transport is around 1.3 MJ/tonne.km (Kempener 2003:45) and emits 1.7e-4 tonne of CO₂/tonne.km (Notten 2001).

In this report, the value of 0.36 ~ 0.67 R/tonne.km for transporting coal will be used. Coal has a density of 1.1 ~ 1.5 tonne/m³ (EB 2006), while raw bagasse has a density of 0.15 tonne/m³ (Bridgwater, Toft et al. 2002) and pelletised bagasse has a density of 0.7 ~ 0.75 tonne/m³ (LAMNET 2001). Due to volume constraints, this implies that the following transport costs will be used⁷⁶:

- raw bagasse: 4.5 R/tonne.km. The caloric value of raw bagasse is 7.1 GJ/tonne (DME 2004:31). The CO₂ emissions per tonne of raw bagasse will then be 1.47e-3 tonne CO₂/tonne.km.
- pelletised bagasse: 0.9 R/tonne.km. The caloric value of pelletised bagasse is on average 17.6 GJ/tonne (LAMNET 2001:1). The CO₂ emissions per tonne of raw bagasse will then be 3.05e-4 tonne CO₂/tonne.km.

The transport costs for pyrolysis liquids or bioethanol can be derived from the cost of fuel oil distribution. In the UK, these are around 3.95 ZAR/ton.km (Bridgwater, Toft et al. 2002:206). However, if the costs for transporting fuel are also much lower as in Europe and the same ratio is applied, a price of around 2 ZAR/tonne.km can be assumed.

⁷⁶ The intermediate values are used to calculate the transport costs.

A2.4. Results

Although there seems to be quite a range of numbers reported in the literature, especially in terms of operational costs for the different technologies, reasonable assumptions can be made for each of the technologies that could potentially contribute to a biomass energy network in KwaZulu-Natal. The technologies and their characteristics are described in table 13. All operational and capital costs are on the basis of a 20 MW installation. The specific operational and capital costs for other scales can be found in the text.

A2.4.1 Learning curves

It is widely accepted that the costs of a process reduce as more units are built and experience accumulates. A learning curve may be observed, which is a fixed percentage reduction in cost per doubling of cumulative production. For example, a learning curve of 20% results in the second plant being 20% cheaper, the 4th plant 36% cheaper than the first plant and the 8th plant 48% cheaper.

In our models, the learning curves should only apply to those technologies that have never or hardly been built before, such as large gasification plants for sugarcane bagasse, large pyrolysis plants or the conversion of sugarcane bagasse into bioethanol. A learning curve of 20% can be assumed for each these technologies (Bridgwater, Toft et al. 2002). In table A2-14, the operational and capital costs are the current projections (without learning curves).

Table A2- 14 Overview of technology characteristics. All numbers are on the basis of a 20 MW installation

	Feedstock characteristics	Product characteristics	Capital costs	Operational costs	Economies of scale	Energy use	Emissions	Capacity limits	Efficiency/yield	Production time (hrs/yr)	Learning curve
Pelletising of bagasse	50 wt% moi. bagasse	10 wt% bagasse pellets	61 R/tonne of bagasse	398 R/tonne of bagasse	YES	85 wh/kg bagasse	0.85 kg co2/kWh [35]	500 MW	0.53 kg pellets/kg bagasse	8000	YES
Combustion of raw bagasse	50 wt% moi. bagasse	Electricity & heat	18.8 mR/MW	200 R/MWh	YES		0.707 ton co2/ton bagasse	500 MW	24%	6480	NO
Combustion of pell. bagasse	10 wt% moi. bagasse pellets	Electricity & heat	18.8 mR/MW	200 R/MWh	YES		0.707 ton co2/ton bagasse	500 MW	28%	8000	NO
Gasification of raw bagasse	50 wt% moi. bagasse	Electricity & heat	30.1 mR/MW	250 R/MWh	YES		0.707 ton co2/ton bagasse	500 MW	40%	6480	YES
Gasification of pell. bagasse	10 wt% moi. bagasse pellets	Electricity & heat	30.1 mR/MW	250 R/MWh	YES		0.707 ton co2/ton bagasse	500 MW	44%	8000	YES
Co-firing of raw/pell. bagasse	50 wt% moi. bagasse	Electricity & heat	0.83 mR/MW	150 R/MWh	NO		0.707 ton co2/ton bagasse	142.5/190 MW	33%	6480/8760	NO

Pyrolysis	30 wt% moi. bagasse	Bioliquids	12.9 mR/MW	563 R/MWh	YES			-	60% g/g odt	8000	YES
Physiochemical production of bioethanol	35 wt% moi. bagasse	99.5 wt% bioethanol + electricity	1.4 mR/m3. day	4 R/ltr.	NO	0.02 diesel/ltr	5.55 kg co2/ltr.	-	0.186 kg ethanol/kg bagasse	8000	YES
Biological production of bioethanol	35 wt% moi. bagasse	99.5 wt% bioethanol + electricity	1.4 mR/m3. day	4 R/ltr.	NO	0.02 diesel/ltr	3.88 kg co2/ltr.	-	0.236 kg ethanol/kg bagasse	8000	YES
Storage of bioethanol /liquids			0.3 mR/m3. day		YES		0	-		8760	NO
Decentralised fuel engine	Minimal 22.4 MJ/kg	electricity	7.9 mR/MW	104 R/MWh	NO		2.22 kg co2/litre of diese	40 MW	45%	8760	NO
Connection to grid	Electricity		695 R/MW	-	NO		0	-	-	8760	NO
Non-grid rural electrification	Electricity		467 R/conne ct.	1500 R/MWh	NO					8760	NO
Grid-con. rural electrification	Electricity		2699 R/conne ct.	450 R/MWh	NO					8760	NO

on											
Road transport bagasse/pe Il.ba	coal			4.5/0.9 R/ton.km	NO	1.31 MJ/t.km	1.7e-4 tonne co2/tonne. km	-		8760	NO
Road transport fuels	Bioethanol or bioliquids			2 R/ton.km	NO	1.31 MJ/t.km	1.7e-4 tonne co2/tonne. km	-		8760	NO

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A3

Operationalisation of scenarios in the bioenergy case study

A3.1 Introduction

This appendix consists of two sections. The first section illustrates how the different 'mental models' forming the basis of the scenarios are operationalised in the decision making process of organisations within the bioenergy network. The second section discusses the operationalisation of risk, trust, loyalty, status, social embeddedness and imitation in the model.

A3.2 Strategic decisions in a bioenergy network

Chapter 7 demonstrated how for a selected number of examples how the different mental models can be operationalised. This section will discuss how all nine different mental models are operationalised and how they affect the outcome of organisational decision making. The mental models are operationalised with regard to two components: 1) a set of processes that describe the translation of the real world into mental representations and 2) the cognitive processes that use this mental representation to inform the decision making process. The first set of processes describe how and which information is used in the decision making process. For example, the mental representation determines which alternative technologies are been perceived as viable options and it determines which potential partners are contacted for buying and/or selling bagasse. The second set of processes determines the decision process; these cognitive processes can either exist out of optimisation rules to maximise utility, 'satisficing rules' determining the required level of return or imitation rules. The next nine section provide a detailed description of the different mental models and their associated processes.

A3.2.1 Industrial network evolution under scenario 1

Scenario 1 (F&R) is informed by a particular a mental model, whereby organisations use functional characteristics to interpret their environment and subsequently choose those options that maximise their utility. The operationalisation of scenario 1 is provided in table A3-1.

Table A3- 1 Operationalisation of scenario 1 (F&R)

F&R	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine costs and efficiencies of all options available	Evaluate utility of each technology and utility of non-action and choose option with maximum utility
<i>Exchange decision</i>	Contact all potential partners available	Evaluate price of each potential partner and choose the partners with the lowest prices

In other words, the organisations determine how much money they would receive from placing the costs for the investment on a bank and they compare this to the returns from investing. They do not consider future uncertainties in terms of, e.g. variation in oil prices or electricity prices. In this mental model, the external world is perceived as static. In terms of partners, they base their decision only on price. For the provinces, scenario 1 means that they prioritise projects on the basis of the connection costs per household and not on the maintenance or life cycle costs.

A3.2.2 Industrial network evolution under scenario 2

Scenario 2 (B&R) constitutes a mental model in which organisations use functional characteristics, as well as individual norms and values to interpret their environment and subsequently choose those options that maximise their utility. The operationalisation of scenario 2 is provided in table A3-2.

Table A3- 2 Operationalisation of scenario2 (B&R)

B&R	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options above the risk threshold and evaluate their costs and efficiencies	Evaluate utility of technology and utility of non-action and choose option with maximum utility
<i>Exchange decision</i>	Contact only trustworthy potential partners	Evaluate price of each potential partner and choose the partners with the lowest prices

For organisations that pursue profit, this mental models means that they only consider technologies that are above their individual risk threshold (see section 7.2.2.1).

Subsequently, they use the same ‘maximising’ strategy to determine if a technology is feasible. In terms of partners, they will only contact those organisations that are perceived as trustworthy, but subsequently base their decision solely on price.

A3.2.3 Industrial network evolution under scenario 3

Scenario 3 (S&R) comprises a mental model, in which organisations use social norms and values to interpret their environment, and subsequently choose those options that maximise their utility. The operationalisation of scenario 3 is provided in table A3-3.

Table A3- 3 Operationalisation of scenario 3 (S&R)

S&R	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options socially accepted and evaluate their costs and efficiencies	Evaluate utility of technology and utility of non-action and choose option with maximum utility
<i>Exchange decision</i>	Contact only potential partners with high status	Evaluate price of each potential partner and choose the partners with the lowest prices

In this scenario, the cognitive processes are similar to the previous two scenarios. However, the way in which organisations perceive their environment is different. Instead of relying on their individual perception of the underlying risk propensity of technology options, organisations base their decision on social norms and values linked to these technologies. Social norms and values are affected by what other organisations have decided. Organisations contract only with those partners that have a high status, but still base their final decision on price.

A3.2.4 Industrial network evolution under scenario 4

Scenario 4 (F&H) is based on a mental model, in which organisations use functional characteristics to interpret their environment and subsequently choose those options that satisfy their aspiration levels. The operationalisation of scenario 4 is provided in table A3-4.

Table A3- 4 Operationalisation of scenario 4 (F&H)

F&H	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine costs and efficiencies of all options available	Evaluate utility of each technology with regard to payback time and choose option that satisfies the condition
<i>Exchange decision</i>	Contact all potential partners available	Evaluate and price and loyalty of potential partner and choose accordingly

In scenario 4, organisations do not try to optimise by choosing those options that maximise their individual utility. Instead, they employ heuristics that, if satisfied, indicate whether or not an option is feasible. In terms of investment decisions, this means that in the case of a ‘functional’ view of the world, organisations determine the costs and efficiencies of each technology and use a payback-threshold to determine whether a technology is feasible or not. Provinces also use heuristics to make their decisions instead of choosing those projects that provide the most connections. In this scenario, organisations use the ‘rule of thumbs’ currently provided to make their decisions, so they evaluate the life cycle costs of each project and prioritise the projects accordingly. For partners, the organisations use heuristics based on loyalty to determine whether a potential partner should be considered.

A3.2.5 Industrial network evolution under scenario 5

Scenario 5 (B&H) constitutes a mental model, in which organisations use functional and individual norms and values to interpret their environment and subsequently choose those options that satisfy their aspiration levels. The operationalisation of scenario 5 is provided in table A3-5.

Table A3- 5 Operationalisation of scenario 5 (B&H)

B&H	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options above the risk threshold and evaluate their costs and efficiencies	Evaluate utility of each technology with regard to IRR threshold and choose option that satisfies the condition
<i>Exchange decision</i>	Contact only trustworthy potential partners	Evaluate price and loyalty of potential partners and choose accordingly

Scenario 5 is similar to scenario 4, except that the organisations use individual norms and beliefs to inform their view of the world. Thus, instead of evaluating all technologies

organisations evaluate only those technologies which risk is perceived as acceptable and they contact only those potential partners that are viewed as trustworthy. The use of risk to evaluate their world has also consequences for the cognitive processes they employ to select appropriate technologies. Because of their perception of risk as an important indicator, organisations use Internal Rate of Return (IRR) – thresholds as aspiration levels rather than payback time. For provinces, this is reflected in the use of ‘maintenance costs’ instead of life cycle costs to prioritise their projects. The use of ‘maintenance costs’ instead of life cycle costs indicates a mental model that perceives the future as uncertain and attempts to minimise the consequences of these potential uncertainties.

A3.2.6 Industrial network evolution under scenario 6

Scenario 6 (S&H) comprises a mental model, in which organisations use social norms and values to interpret their environment and subsequently choose those options that satisfies their aspiration levels. The operationalisation of scenario 6 is provided in table A3-6.

Table A3- 6 Operationalisation of scenario 6 (S&H)

S&H	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options socially accepted and evaluate their costs and efficiencies	Evaluate utility of each technology with regard to IRR threshold and choose option that satisfies the condition
<i>Exchange decision</i>	Contact only potential partners with high status	Evaluate price and loyalty of potential partners and choose accordingly

Scenario 6 uses social norms and values to interpret the environment and uses subsequently heuristics to choose between the alternatives available. For investment decisions, organisations use an IRR-threshold and for choosing partners they are informed by their loyalty feelings towards the potential partners.

A3.2.7 Industrial network evolution under scenario 7

Scenario 7 (F&I) is based on a mental model, in which organisations use functional characteristics to interpret their environment and subsequently choose imitate the organisations that performs best in terms of utility. The operationalisation of scenario 7 is provided in table A3-7.

Table A3- 7 Operationalisation of scenario 7 (F&I)

F&I	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine costs and efficiencies of all options available	Choose technology by imitating organisations that has the highest utility
<i>Exchange decision</i>	Contact all potential partners available	Choose partners on the basis of highest status .

In scenario 7, organisations do not make ‘rational’ decisions anymore, but they imitate others. Under these circumstances, an organisation does not attempt to evaluate the consequences of their actions, but they imitate others. In scenario 7, organisations still perceive their environment through ‘functional’ characteristics, so they imitate the organisations performing best in terms of the individual utility of the imitator. If there are no other competitors in the network, however, they will use their individual cognitive processes to make a decision. For the choice of partners, organisations do not attempt to base their decision on price, but they choose those organisations that have a higher status than others.

A3.2.8 Industrial network evolution under scenario 8

Scenario 8 (B&I) constitutes a mental model, in which organisations use functional and individual norms and values to interpret their environment and subsequently imitate those options that are chosen most frequently in the network. The operationalisation of scenario 8 is provided in table A3-8.

Table A3- 8 Operationalisation of scenario 8 (B&I)

B&I	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options above the risk threshold and evaluate their costs and efficiencies	Choose technology by imitating the technology that is used most frequently in the network
<i>Exchange decision</i>	Contact only trustworthy potential partners	Choose partners on the basis of highest status .

In scenario 8, organisations also imitate, but they imitate on the basis of the frequency that a technology is used rather than imitating the ‘best’ performer. Haunschild & Miner

(1997) found that imitation behaviour on the basis of frequency rather than individual performances indicates organisational behaviour that perceives a higher level of uncertainty in the environment. In their own words, “uncertainty enhances frequency imitation” (Haunschild and Miner 1997:472). The choice for potential partners in this scenario is affected by individual risk perspective of the organisations and by the status of the organisations in the network.

A3.2.9 Industrial network evolution under scenario 9

Finally, scenario 9 (S&I) is based mental model, in which organisations use social norms and values to interpret their environment and subsequently imitate those organisations that have the highest status in the network. The operationalisation of scenario 9 is provided in table A3-9.

Table A3- 9 Operationalisation of scenario 9 (S&I)

S&I	<i>Mental representation</i>	<i>Cognitive process</i>
<i>Transformation decision</i>	Determine options socially accepted and evaluate their costs and efficiencies	Choose technology by imitating the organisation with the highest status in the network.
<i>Exchange decision</i>	Contact only potential partners with high status	Choose partners on the basis of highest status .

The final scenario reflects a situation where organisations perceive very high levels of uncertainty in their environment. Therefore, they use implicit social network characteristics to ‘make sense’ of their environments and they imitate rather than make individual decisions. This situation is reflected by the rules in table A3-9. Organisations only evaluate those technologies that are socially acceptable and they only contact those organisations with a high status. In terms of cognitive processes, they imitate organisations with a high status rather than looking at the frequency of technologies adapted and they choose partners on the basis of their status instead of the received price.

A3.3 Operationalisation of interpretation and decision rules

The previous section has described the set of rules that are used to distinguish nine different mental models and their associated perceptions towards the inherent uncertainty associated with strategic decision making. Some of these rules are rather straight forward and will not be discussed in more detail. For example, the rule that govern rationality simply consist of a maximisation rules that evaluates the return of each alternative (including the alternative to not invest or exchange) and subsequently chooses the alternative with the highest return. However, other rules require further interpretation for implementation within the bioenergy case study. The following rules will be discussed in more detail:

1. the interpretation of technology risks and its impact on strategic decision making;
2. trust and loyalty and their impact on the decision making process;
3. status and its impact on the decision making process;
4. social embeddedness and imitation.

A3.3.1 Operationalisation of technology risk

In industrial networks, there are several forms of risk associated with the newness of a technology and how it might impact on an organisations decision to either adopt or reject the technology (Rogers 1995:161). Freeman and Soete (1997) considered two forms of uncertainty associated with new technologies; 1) technical uncertainty and 2) market uncertainty. Both uncertainties can be interpreted as part of the mental model frameworks developed in chapter 5, whereby technical uncertainty determines whether an organisation is willing to consider a particular uncertainty as a potential alternative for its strategic decision making process (the mental representation) and whereby market uncertainty determines what the minimum returns of a technology should be in order to adopt the technology. The first process can be reflected in a threshold value consisting of an individual norm, whereby organisations will only consider a technology if the risk profile associated with that technology is above the individual threshold of the organisation. Market uncertainty, on the other hand, is associated with the acceptance threshold after evaluating a technology. If the market uncertainty associated with a

particular technology is high, the organisation will require higher returns than when market uncertainty is low⁷⁷.

The use of individual norms to determine which alternative technologies should be considered is implemented in scenario 2, 5 and 8. These scenarios represent mental models in which individual norms and value impact on how organisations perceive the world. The use of heuristics consisting of aspiration levels to reflect upon the market uncertainty of a technology is implemented in scenario 3, 4 and 5. Recall that these three scenarios represent mental models in which organisations use heuristics to inform their decision making process.

The following methodology is used to implement individual norms of organisation associated with technical uncertainty of new technologies. Firstly, each technology is associated with a particular risk profile, as illustrated in figure A3-1.

The exact risk profiles should be determined in conjunction with stakeholders within the industrial network. In this case, the profiles are created on the basis of informed judgement by the modeller.

⁷⁷ Howard (1988) found empirical evidence for heuristics used in decision making, which are used to deal with uncertainty. According to his findings, organisations will not invest in technologies that cost more than 1 to 1,5 their total annual income. This rule is not implemented in this thesis, because it would require modelling the income streams of sugar production of the sugar mills and it would require to model potential income streams from new investors entering the South African market..

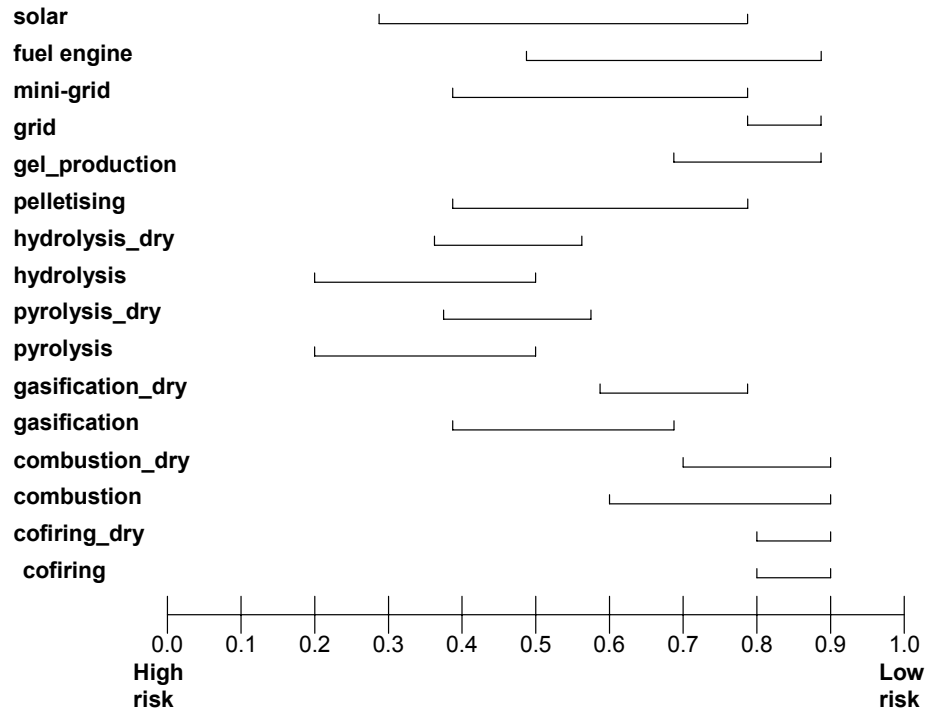


Figure A3- 1 Risk profiles of technologies explored in the bioenergy network

Each technology has a risk profiles associated with it, whereby 1 represents very low risk technology and 0 represents very high risk technologies. The high end of the risk profiles represent the risk profile associated with small-scale projects, while the lower end of the scale is associated with technologies that are implement on a large scale. For example, the implementation of a single solar system has a risk profile of 0.8, while a project that electrifies a total municipality with solar systems has a risk profile of 0.3. An organisation will consider a technology if its associated risk profile is above its individual norm for risk⁷⁸.

If an organisation is considering a particular technology, the aspiration level within the heuristic that determines whether a technology is accepted will depend on the risk profile of the technology. This process is implemented as follows. Firstly, a convex value function is used to determine the exact level of risk from the perspective of the organisations. A convex value function reflects risk aversiveness of people and organisations (Tversky and Kahneman 2000). Subsequently, this value is used to

⁷⁸ The risk profiles of organisations can change through ‘learning by doing’ (not implemented) and the individual norms associated with risk can change due to social institutions (see A3.3.4).

determine the exact aspiration level for a particular technology. In scenario 3, organisations use payback time as aspiration levels. The payback time associated with a technology is determined by relating the risk perception to the minimum and maximum payback times accepted for new technologies. For example, if the risk perception of a technology is 0 (high risk), then the payback threshold associated with this technology is 2 years. If a technology is associated with low market uncertainty (risk value = 0), then a payback time of 8 years is accepted. The similar procedure is used in scenario 4 and 5. Instead of payback threshold, organisations use IRR-thresholds as aspiration levels. The lowest IRR-threshold is 10%, while the highest IRR-threshold is 35%. These IRR-threshold are lower and upper limits used in investment projects (Peters, Timmerhaus et al. 2003)⁷⁹. Thus, a project associated with low risks will be accepted if it has a higher internal rate of return than 10%, while a high risk project will only be accepted if its returns are higher than 35%.

A3.3.2 Trust and loyalty

The modelling of trust and loyalty has been discussed in detail in section 3.6.2.1. in chapter 3. In summary, trust is modelled by using partial value functions for the following characteristics: status, past experience, conflict and benevolence. The operationalisation of status uses a global range involving all organisations in the network to determine the value of status for each potential partner. The other characteristics, past experience, conflict and benevolence, are determined by evaluating the local range of these characteristics for all potential partners and subsequently valuing the characteristics of individual partners accordingly. The weights for each characteristic are equal. Weights do not only reflect how strongly an organisation feels about any of these criteria, but they also reflect a scaling constant for differences in the length of the intervals scales. However, since the scales for past experience, conflict and benevolence all depend on the number of potential contracts that could have existed between organisations, the interval scales for each criteria are similar. The trustworthy threshold is set at 40%, which means that, from all potential partners, only the top 40% are perceived as trustworthy. Clearly this is an arbitrary setting, but still allows adequate demonstration of the approach within the context of this case study.

⁷⁹ Peters, Timmerhaus et al. (2003 provide 'rules of thumb' for building chemical plants, where 10% is used for secure projects and 35% is used for risky projects.

Loyalty is modelled on the basis of two characteristics, namely the length of the relationship, and benevolence. In a similar manner to the means by which trust is considered, local ranges are used to value these characteristics and their weights are assigned to be equal to each other. Loyalty, itself, is presented as a value between 0 and 1 for each organisation, whereby a value of 1 suggests that the organisation is willing to compensate up to 20% on price⁸⁰, while a value of 0 indicates no compensation for loyalty.

A3.3.3 Status

The perceived status of organisations plays an important role in the institutional and imitation processes which develop within the network. Firstly, status plays a role in the decision of organisations to choose partners. Clearly, high status partners are preferred over partners with a low status (see scenario 3, 6 and 9). Status is determined by two characteristics: the size of the organisation and the number of relationships it chooses to exercise. "Size" is determined relative to a global scale ranging 0-1, where 0 is the smallest size, and '1' represents the maximum size, determined by the organisation with the highest capacity installed. The number of relationships is valued according to the total number of relationships possible for each organisation. Both size and number of relationships are valued equally in the decision. Secondly, status plays a role in the establishment of social norms and values related to the adoption of new technologies. Those technologies adopted by organisations with the highest status become socially accepted by other organisations, overruling potential individual norms these organisations would have employed (see section 7.2.2.1) in the absence of such social embeddedness.

A3.3.4 Institutionalisation and imitation

It is important to stress that institutionalisation and imitation are two different processes, which play different roles in mental models. Institutionalisation is a process that affects the mental representation of organisations. It determines which information or alternatives is/are considered. Imitation, on the other hand, is a cognitive process that directly determines the actions of an organisation.

⁸⁰ The use of a 20% as a loyalty premium was confirmed at a presentation of this work at an industrial conference, where visitors suggested that these loyalties ranged between 10 and 20%.

Imitation can only occur where two or more organisations have the same function within the system. This breaks the list of organisations essentially into two groups – those that generate electricity and/or biofuels; and those providing infrastructure (concessionaires and provinces). The first category can imitate each other with respect to the technologies they adopt for generating bioenergy, while the second category of organisations can imitate each other in terms of infrastructure technologies. But what of the initial condition in the network? Since the bioenergy network does not exist at the moment⁸¹, it could never evolve if all organisations imitate each other from the start. Therefore, the scenarios that model imitation assume that organisations use individual heuristics to make decisions until one of the organisations decides to invest and the bioenergy network starts to evolve.

Similarly, institutionalisation cannot take place before there is at least one or more organisations that initiate the development of a bioenergy network. Therefore, the scenarios that model institutionalisation will be based on individual norms until one or more organisations kickstarts the bioenergy network. Processes of social institutionalisation are represented in scenario 3, 6 and 9 and they impact on the individual norms of organisations used to determine which technologies will be considered as viable alternatives. Two processes social institutionalisation take place: one process for the organisations that are involved in generating bioenergy and a second process for organisations working on infrastructural developments. Social institutionalisation is operationalised by setting reducing the individual norms for those technologies that have been adopted by other organisations within the network. This does not necessarily mean that an organisation will therefore adopt that particular technology (unlike imitation behaviour), but the organisation will at least consider these technologies in its own decision making process. The decision itself still depends on what cognitive processes the organisations use to make their decisions.

⁸¹ At the time of printing this thesis, one sugar mill has started producing green electricity using combustion technologies. This is likely to expand considerably in 2008, as ESKOM (the parastatal utility) has called for bids for electricity to be produced from bio-sources, and the sugar mills are to the forefront of this initiative.

A3.4 References

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3. Peters, M. S., K. D. Timmerhaus, et al. (2003). Plant Design and Economics for Chemical Engineers. Boston, McGraw-Hill.
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Modelling results

A4.1 Introduction

This appendix consists of five sections. The first section provides the full modelling results of the 9 scenarios that have been explored in the ‘business as usual scenario’. The second section includes the functional and structural performance profiles that have been used to characterise sustainable development of different evolutionary pathways. The third section provides the full modelling results of the 3 governmental interventions that have been explored and the fourth section presents the full modelling results of the impacts of changed strategic behaviour on the network evolutions. The final section presents an overview of the modelling results that have been produced by combining the agent-based modelling scenarios with global dynamic optimisation models.

A4.2 Modelling results for BuA context scenario

Figure A4-1 illustrates the different potential bioenergy network evolutions associated with different agent scenarios within the context of a ‘business as usual’. The top row shows the results of scenario based on mental models involving rational decision rules (1 to 3), the middle row shows the different scenarios based on mental models with heuristics (4 to 6) and the bottom row represents the scenarios that are based on cognitive rules of imitation (7 to 9). The vertical columns represent (from left to right) mental models that use functional information for mental representations, individual norms and social embeddedness.

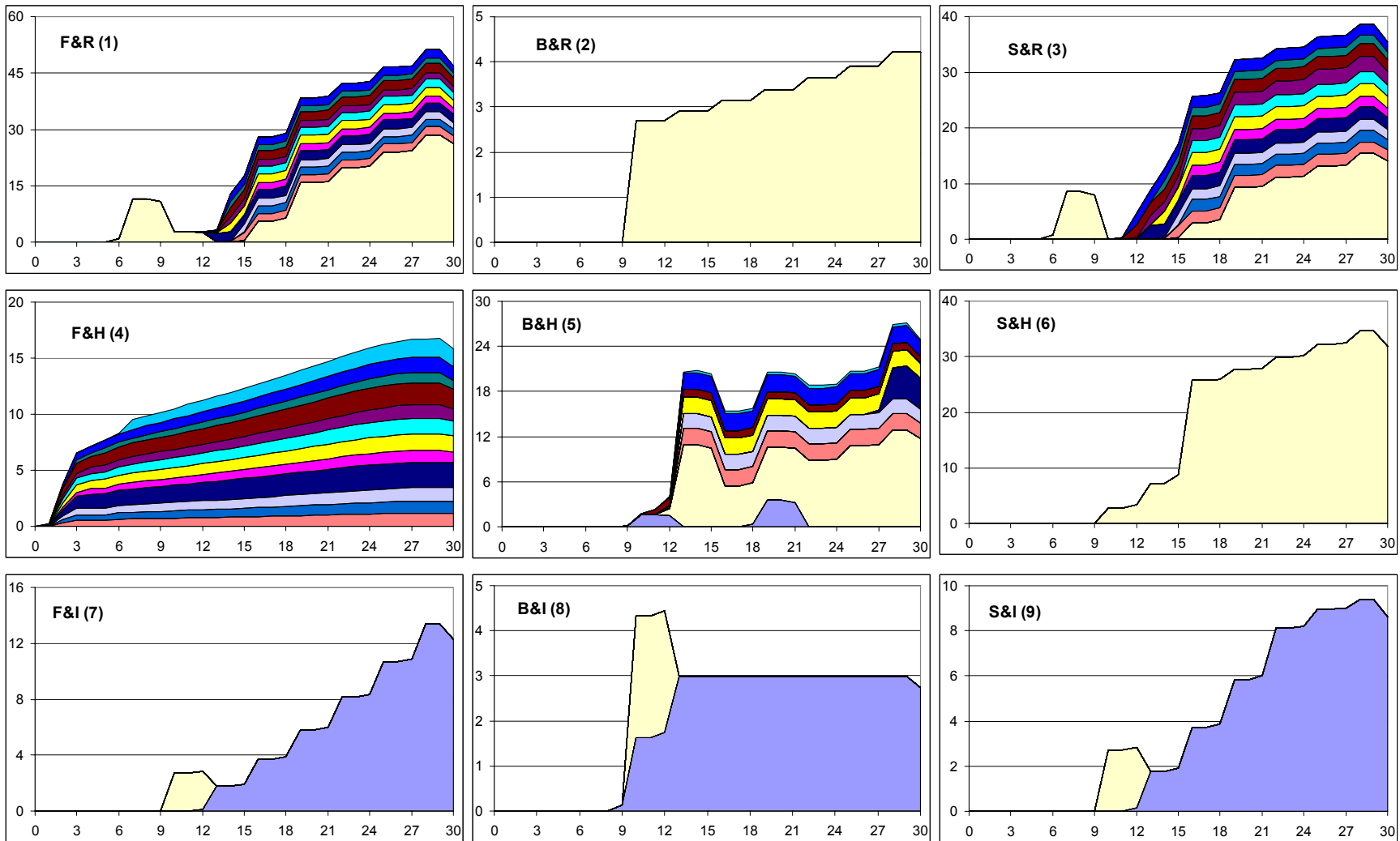


















Figure A4- 1 Energy production in PJ by the different organisations in the bioenergy network over a 30 years (legend next page)

	SM12
	SM11
	SM10
	SM9
	SM8
	SM7
	SM6
	SM5
	SM4
	SM3
	SM2
	SM1
	GEL
	IFP
	IEP
	IPP
	Generator

The modelling results show a large variety in the different evolutionary pathways that are possible within the 'business as usual context'. The results differ in terms of when the bioenergy network start developing, the number of organisations involved and the energy provided. There are also large differences in the efficiencies by which the networks convert bagasse into energy. Some evolutionary pathways only produce about 4 PJ p.a. (scenario 2), while others produce almost 40 PJ p.a. (scenario 3 & 6). The reason for these large differences is the important role of mental models on the network evolution. The results clearly show that depending on how organisations perceive the world and how they make their decisions, industrial networks can evolve in completely different directions.

In none of the scenarios, independent power producers or independent biodiesel producers enter the network. Despite this, they do affect the network evolution through the effect they have on the price for wet and dry bagasse. Without the potential threat of other independent power producers entering the network, the

existing organisations could bargain lower prices. A secondary effect of the emergence of a local market for wet and dry bagasse is that it affects the decision making of the sugar mills in the network. In a network where there would be no potential entrance of independent power or biofuel producers, the value of the bagasse is equal to the price that the pulp and paper industry is willing to pay for its fibre content. However, as soon as independent power producers enter the network, bagasse becomes a valuable commodity. From that point onwards, sugar mills have to consider opportunity costs associated with using bagasse within the sugar mill. In other words, the sugar mills have to consider that by using the bagasse internally they miss out on potential revenues from selling the bagasse to independent producers. Such considerations change the economics of their own decisions to invest in localised power production facilities.

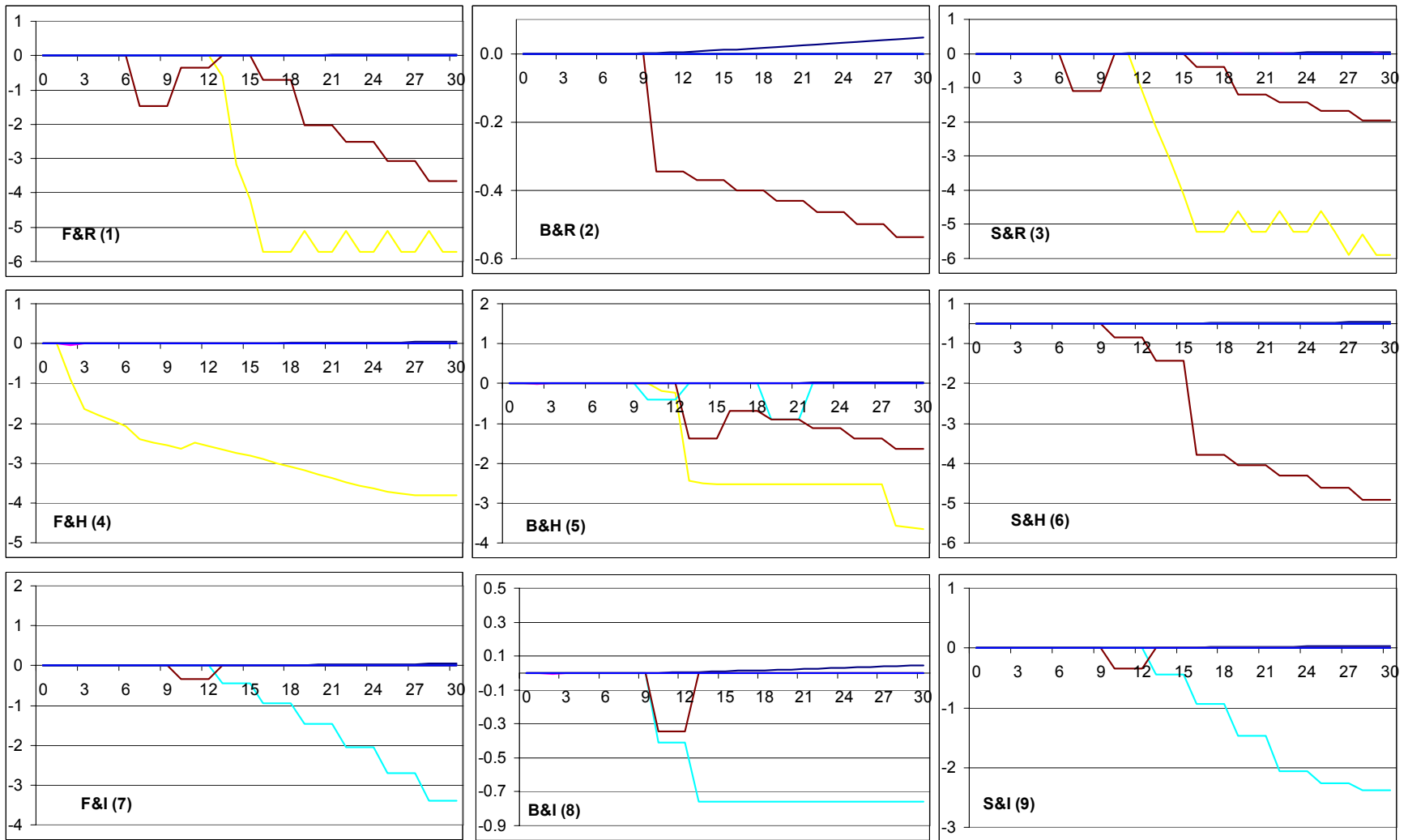


Figure A4- 2 CO2 aversion (M tonnes) by different organisations in the bioenergy network over a 30 years (legend next page)

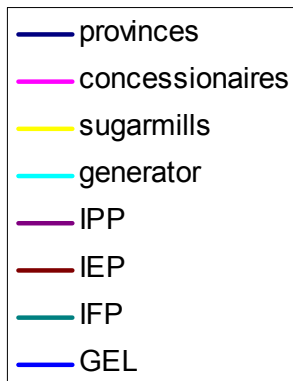


Figure A4-2 shows the CO₂ emissions that are averted by the different organisations in the network. The positive emissions from the provinces are associated with their use of diesel to feed the fuel engines of mini-grids. These graphs show the important effects of transportation of, wet or dry bagasse and the associated CO₂ emissions. In those network evolutions where the IEP uses wet bagasse for hydrolysis, the total CO₂ emissions reduction is minimal, while the transport of dried

bagasse still reduces CO₂ emissions by a factor of 2. For example, scenario 4 produces only 20 PJ of energy in year 30 in comparison to 40PJ in scenario 6. However, scenario 4 reduces twice as much CO₂ emissions as scenario 6 through decentralised production of electricity.

The differences in the infrastructures that are developed as a consequence of different mental models are not as clear as those differences which manifest in the generation side of the bioenergy network. The most important reason is that infrastructure is dominated by the provinces and their policies. Each province receives a yearly allocation for new infrastructure, which determines the extent to which they can build new connections. The concessionaires have more freedom; however their decisions are also affected by the circumstances of the municipalities in which they operate.

There are still some interesting patterns to be observed if one considers the effect of using different mental models. For example, in scenario 1 and scenario 5 the same number of connections have been made, and the same technology mix (grid, minigrig via engines and minigrig via sugarmills) have been used to electrify households in the various municipalities. However, by using different cognitive rules, the choice of which municipalities to electrify can change quite substantially. Figure A4-3 shows the number of connections and the electrification patterns for the 58 municipalities in KwaZulu-Natal. The figures show that in scenario 5 municipalities are completely electrified one by one (the electrification rate of those municipalities goes to 1 within a particular time step, indicated by a vertical line), while in scenario 1 the municipalities are electrified much more gradually.

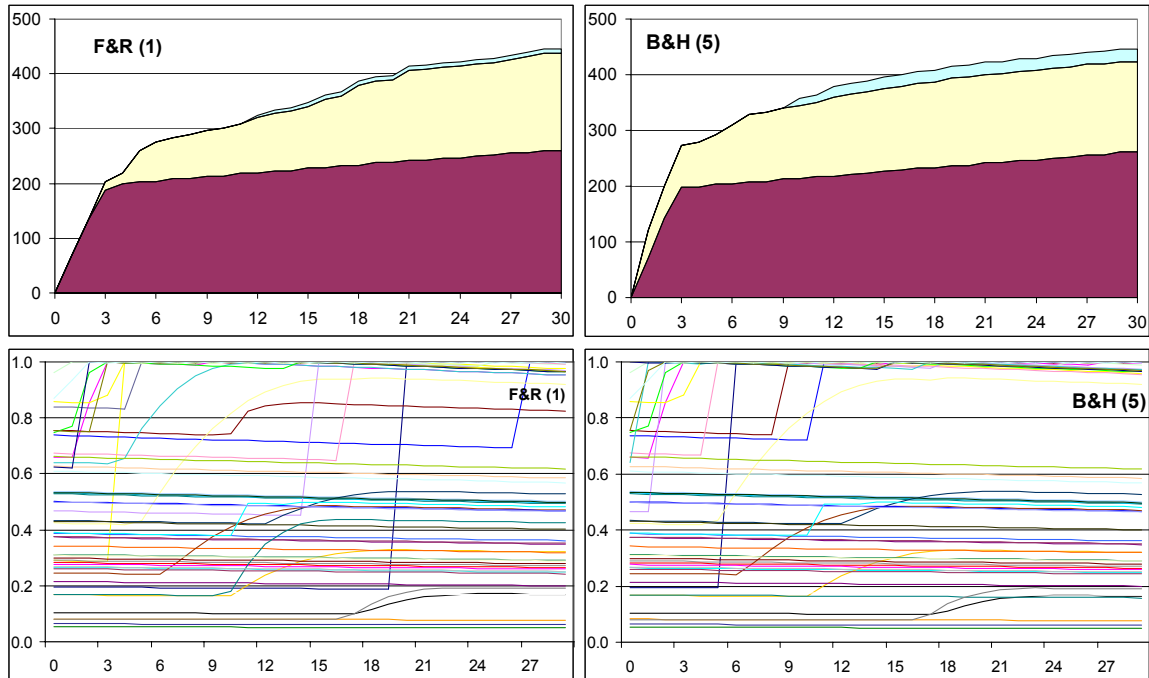


Figure A4- 3 Electrification of KwaZulu-Natal in connections (x1000) per technology and in electrification percentage in each of the 52 municipalities over 30 years

Another model output is the number of household connections per province or concessionaire. Figure A4-3 shows the different evolutionary pathways for both provinces and concessionaires. The modelling results of infrastructure development do not present the same diversity between the different scenarios as the energy production profiles. Most infrastructure developments are dominated by a large number of household connections in Ethekwini, which is the local government in which the capital Durban is located and which has the highest household density. Furthermore, the results show that most local governments are involved in the electrification of their municipalities. The reason for the little impact that different mental models have on the infrastructure development is that actions of local governments are dominated the infrastructure development funds. Their actions are mostly based on the amount of annual MIG allocation they receive, and their evolution is therefore less dependent on the evolution of the other system structures. Furthermore, their decision making rules are restricted by regulation and therefore less dependent on their mental representations of the world. However, there are some general patterns that can be observed. It can be observed that different evolutionary pathways have different times of rapid growth (mostly around year 8 and year 16). This can be explained by the fact that the

development of mini-grids without participation by the mills themselves requires investment in fuel engines. Annual MIG allocations are not sufficient for these large-scale investments, so they will save their allocations for several years to invest in engine capacity. After such investments, these provinces show a rapid growth in the number of household connections in a particular region. The investment hurdle for infrastructure development is thus a substantial constraint for the development of the bioenergy network. Furthermore, it suggest that incremental funds are not necessarily the best way to increase the electrification rates of rural South Africa. The yearly funds lead to incremental improvements on existing connections or marginal growth along the existing grid lines. Instead, large scale funding is required to address the most vulnerable regions of KwaZulu-Natal.



There are many other modelling outputs that can be shown, each providing interesting narratives on how the bioenergy model might evolve into the future. For example, the role of oil prices is very important in the network evolution. In scenario 2, as shown in figure A4-4, the IEP establishes itself within the network, but only uses a limited amount of bagasse (only from one sugar mill) to feed the hydrolysis plant. The bioethanol plant is commercially most attractive in year 9, because of rising oil prices and therefore rising bioethanol prices. However, the IEP is restricted in that it cannot transport bagasse from other sugar industries over a longer distance, because of the associated transport costs. The establishment of an independent power producer in the network restricts the possibility for sugar mills to start producing locally, because in-house use of bagasse will need consideration of the opportunity costs.

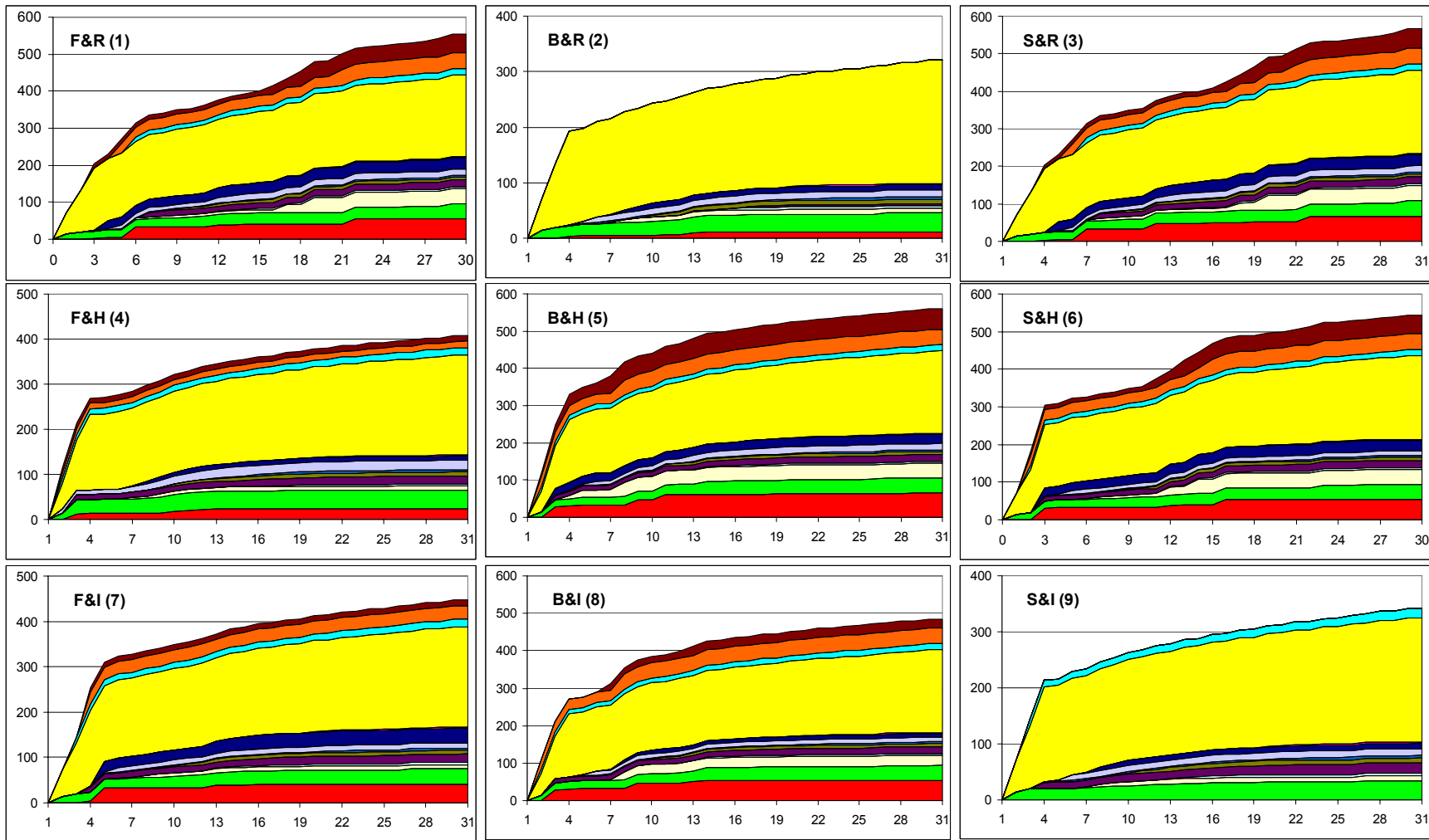


Figure A4- 4 Total household connections (x 1000) by local governments and concessionaires in the bioenergy network over a 30 years (legend previous page)

A4.3 Modelling results for evaluating sustainable development

Chapter 7 discussed in detail the use of functional and structural indicators for the evaluation of sustainable development of different evolutionary pathways. Furthermore, it coupled the use of these indicators back to the challenges that were identified in chapter 4. This section provides a full overview of the functional and structural performance of the nine scenarios that have been explored in the 'business as usual' context.

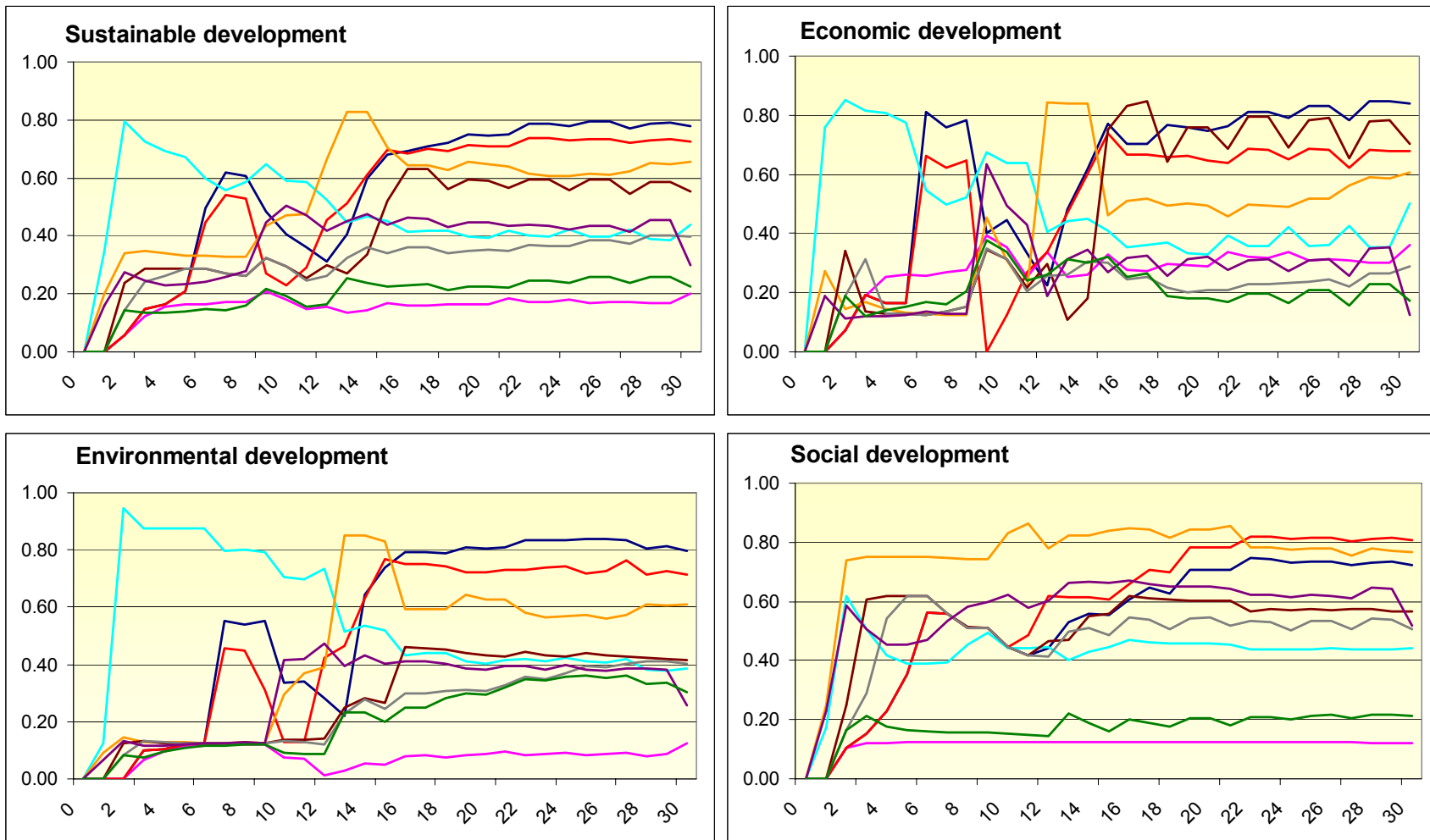


Figure A4- 5 Indication of sustainable development of 9 different scenarios (legend next page)

- F&R (1)
- B&R (2)
- S&R (3)
- F&H (4)
- B&H (5)
- S&H (6)
- F&I (7)
- B&I (8)
- S&I (9)

The indicator for sustainable development is constructed by giving the economic, environmental and social development each a weighting of 0.33. These figures provide some indication on which scenarios are more preferred in terms of sustainable development than others. For example, scenario 1, 3 and 5 perform, on average, better than any of the other scenarios, especially in terms of social and environmental performance. Coincidentally, scenarios 1,3 and 5 are the only 3 scenarios where both sugar mills and an independent power producer operate in the network. Scenario 6, on the other hand, seems to have the best overall economic performance, while scenario 4 provides highest benefit at the start of the network evolution.

The graphs of economic, environmental and social development score are themselves constructed by adding up the functional and structural performance for each of the scenario within a particular year within each of the three evaluation categories (economic, environmental and social). This reflects the view that a network with a low functional contribution can be compensated for by a high score in structural performance. These results are shown in figure A4-6. The functional performance is calculated by normalising the contributions made of one scenario against the performance of the other scenarios in that particular year. This means that the functional performance of a network at any particular year is valued relative to the functional performance obtained in any of the other evolutionary pathways. In other words, the network that provides the highest functional performance in a particular year receives a value of 1, while the network with the lowest functional performance in that particular receives a value of 0. The normalisation procedure for any particular year reflects the view that functional performance can be evaluated independently from the context in which the network operates. The structural performance is calculated by aggregating the systems score on efficiency, effectiveness, resilience and adaptiveness using equal weightings. It can be seen in figure A4-6 that the functional contribution of a particular evolutionary pathway depends on the performance of the other evolutionary pathways in that particular year. In scenario 4, for example, the bioenergy network scores highest in terms of environmental and economic contributions and also second highest in terms of social contributions. However, the system fails to deliver the same benefits as other networks that have been developed more gradually and perform better into the future,

despite its gradual growth in energy production (recall figure A4-1). This is a very important finding for those decision makers whose primary focus is the stimulation of sustainable development. Furthermore, figure A4-6 shows that on the basis of an aggregated structural performance it is not possible to prefer or differentiate one scenario over another scenario. This suggests that from a structural point of view, it is important to distinguish different structural features explicitly, because in aggregated form they lose their meaning.

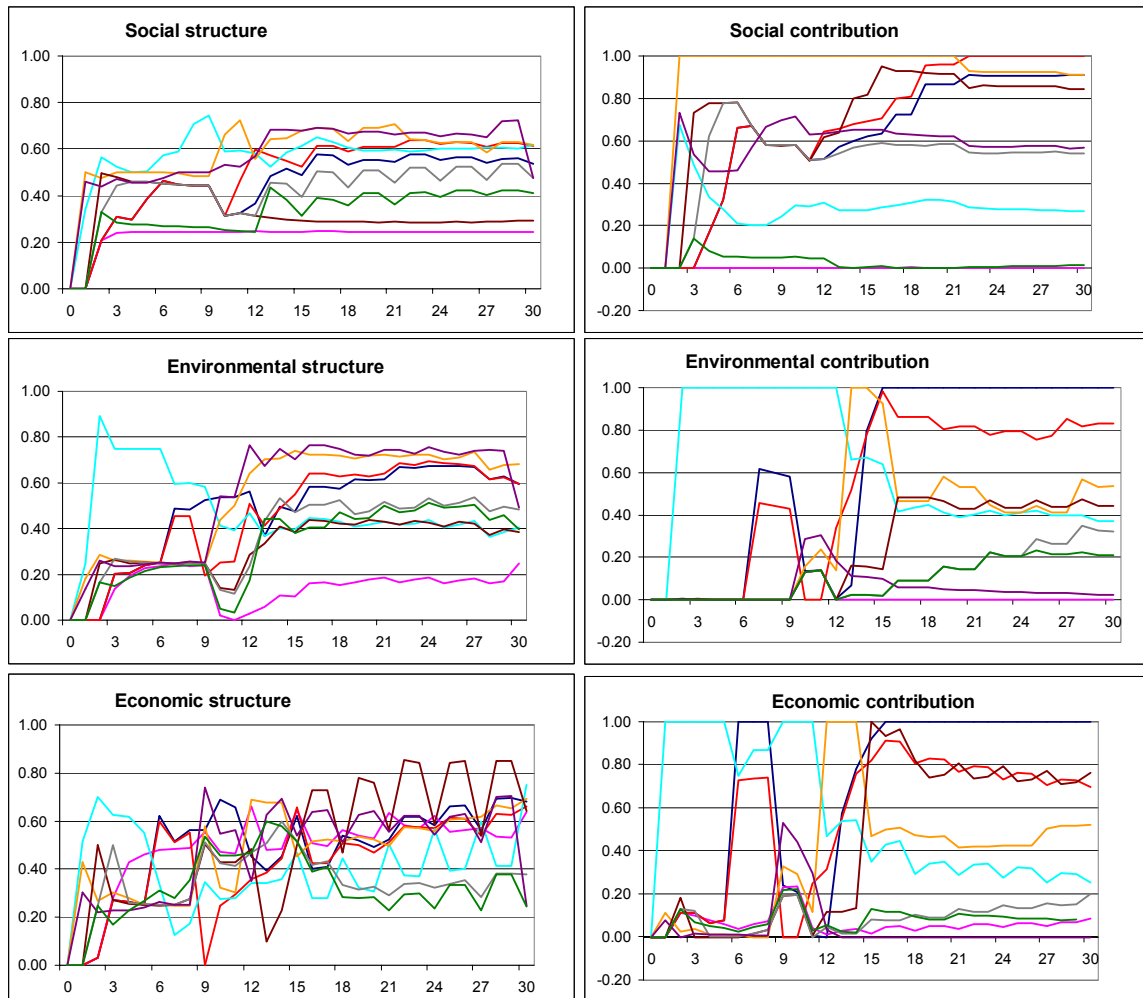


Figure A4- 6 Structural performance and functional performance for the economic, social and environmental contribution of the energy network (legend previous page)

The next three figures illustrate the efficiency, effectiveness, resilience and adaptiveness of the bioenergy network evolutions in each of the three main assessment criteria; i.e. economic, environmental and social.

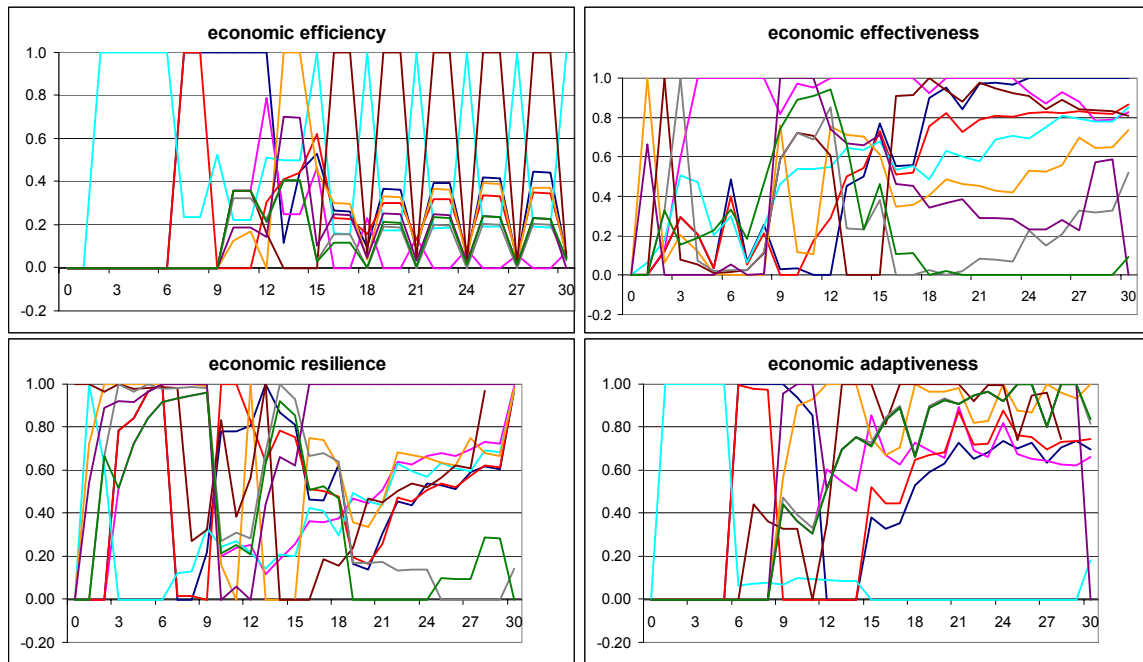


Figure A4- 7 Structural features of the economic performance of evolutionary pathways

The results show that there can be a distinct trade off between resilience and effectiveness (see for example scenario 7 & 8). In scenario 7, an increased effectiveness reduces the resilience of the system, while in scenario 8 a high resilience reduces the effectiveness of industrial networks. This becomes increasingly apparent at later phases in the network evolution, where the full capacity of the network is used to produce energy.

However, the trade-off between resilience and effectiveness is not necessarily the case. Those networks that continuously grow, for example scenario 3, can couple resilience to effectiveness. Another observation is that efficiency is not a good indicator for economic performance, because it highly dependent on the prices of resources and outputs. The regular pattern shown in the economic efficiency of the bioenergy networks coincides with 3 yearly contract period in which organisation end their existing contracts and look for new contracts (see 6.4.3.). The results for resilience show that those evolutionary pathways that are dominated by the sugar mills (1, 3, 4, and 5) have lower resilience than the evolutionary pathways that are dominated by the entrance of independent power producers. The reason for this is that, although participation of sugar mills

increases the number of organisations in the network, they all operate on maximum capacity. Thus, a failure of one organisation, either through internal or external forces, immediately leads to failure in the delivery of economic contribution of the system. Finally, the results show that there is no correlation between the economic resilience of a system and the economic adaptiveness of a system, which supports the initial assertion that the ecological use of resilience does not accurately reflect socio-economic systems and their characteristics. Scenario 4 shows low adaptiveness in comparison to the other scenarios. Although scenario 4 consists of a large number of organisations, they are all sugar mills and all use the same technologies. In cases where there is a shift from the need for electricity to the need for biofuels, this evolutionary pathway is very vulnerable. This is reflected in the indicator for economic adaptiveness.

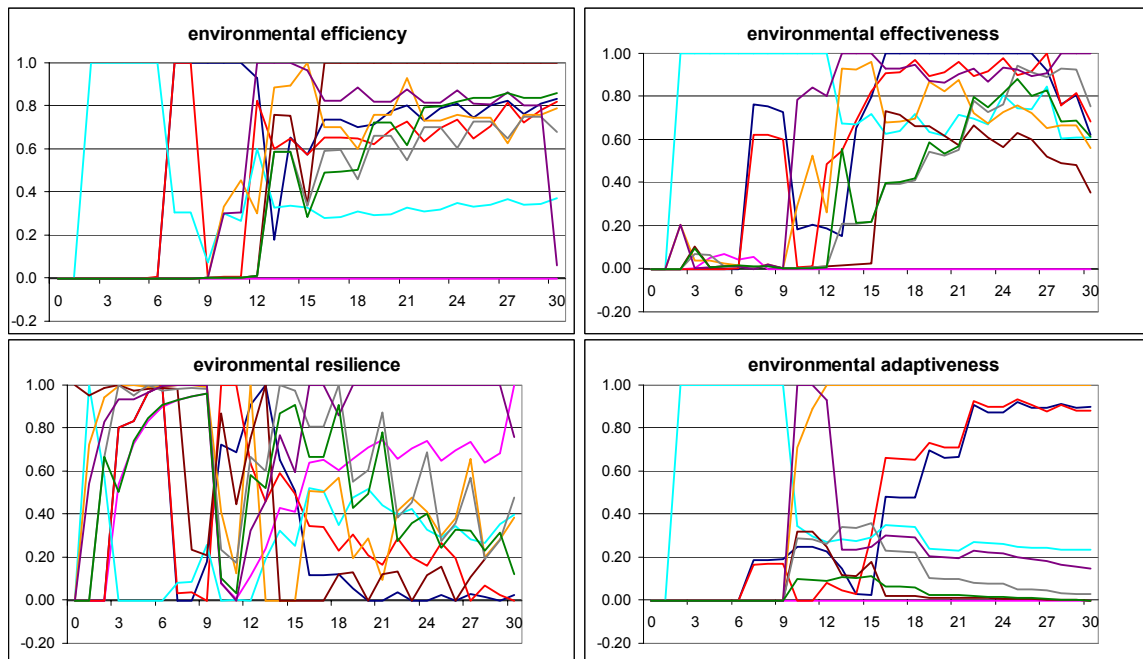


Figure A4- 8 Structural features of the environmental contribution of bioenergy network evolutions

Figure A4-8 shows the structural features of the environmental contribution of bioenergy. An interesting feature of the environmental performance is that in all four structural features there is a clear distinction between evolutionary pathways that develop early throughout the 30 year time period and those evolutionary pathways that gradually improve the structural features of the system. In particular, a distinction can be made between scenario 4 on the one hand and most of the other evolutions on the other hand.

Scenario 4 involves a large number of sugar industries that decide to use wet bagasse for the production of electricity. However, this pathway is **locked into** its initial structure as generating technologies have a life time of more than 20 years. This means that sugar mills are unable to adapt their infrastructure to increased availability of bagasse or to accommodate for technologies with higher efficiencies (ie gasification). Scenario 8 is, from this perspective, similar to scenario 4. Although scenario 4 and 8 have completely different structures in terms of the technologies that are employed and the organisations that are involved, they are both locked into a very efficient and effective structures with limited capability to future challenges, either in the form of shocks or shifts. Finally, scenario 8 is interesting, because it is the only evolutionary pathway that ceases to exist. In year 27, the only sugar mill that provides (dried) bagasse to the generator decides that it is not financially attractive to build a new pelletiser. The following contract period the generator uses wet bagasse to cofire, however the increasing transport costs make this financially unviable in year 30. Thus, in the last year of the analysis the generator decides that stop purchasing bagasse and the bioenergy network ceases to exist.

Figure A4-9 shows the structural features of the bioenergy network in the context of its social contribution. The pathways for the structural features of the network are different from the previous pathways, because they relate to the structural features in the network that provide electricity and biogas to households. The social efficiency and social effectiveness are similar for most evolutionary pathways, mainly because the MIG allocation is an important determinant in how provinces make decisions, regardless from their mental models. The networks that are more effective and efficient are those that provide electricity in an efficient way (ie decentralised production of electricity and/or an independent power producer operating on full capacity). However, there is a large variety in terms of the resilience of the different infrastructures for electrifying households. An increased resilience is related to an increase in the number of households that are connected with the grid, because grid connections provide the largest capacity for electricity distribution (although it not necessarily means that a large capacity for the delivery of green electricity will result in the production of green electricity. It also is related to the capacity for the production of green electricity. Scenario 2 has the highest resilience in terms of connecting households, because there no production capacity for electricity. Scenario 4, on the other hand, shows the lowest resilience. Although scenario 4 also employs grid connections, it is the only evolutionary

pathway in which households are connected to solar systems. The use of solar systems reduces the resilience of the system, because they are stand-alone systems that present no excess capacity in case one or more solar systems malfunction. A temporary shock to any of these systems will immediately disrupt the provision of electricity to those households connected to the solar systems. Thus, although scenario 4 has one of the highest environmental contributions of any evolutionary pathway, it comes at a cost of reduced resilience.

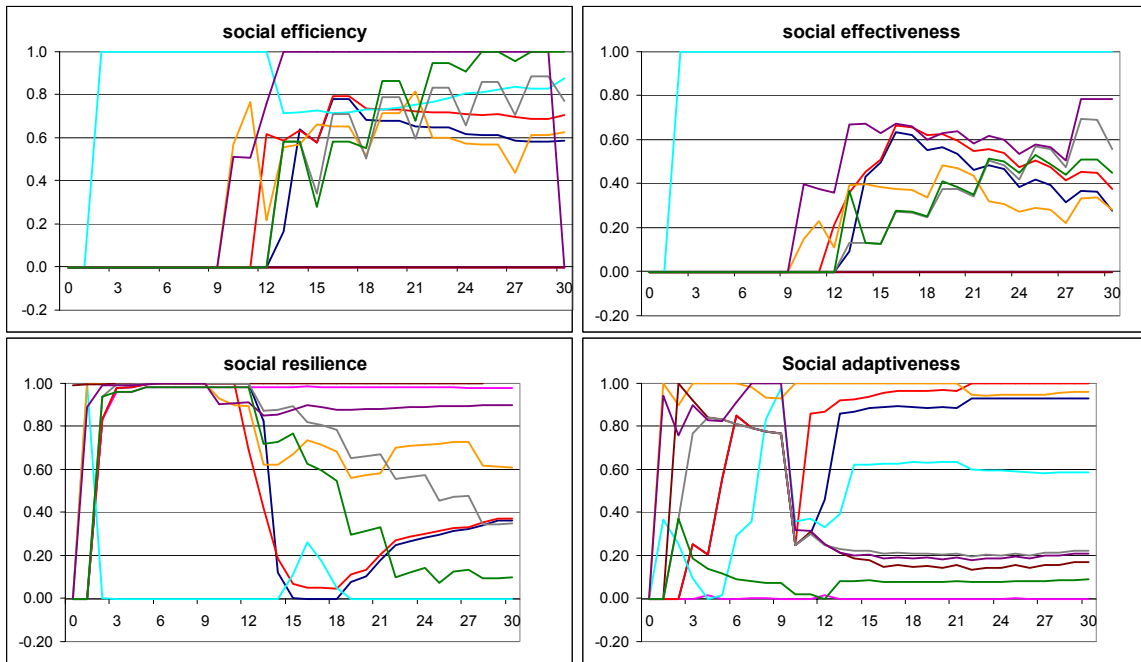


Figure A4- 9 Structural features of the different evolutionary pathways for the social contribution of bioenergy networks

Figure A4-10 shows the difference between scenario 2 with the highest resilience and scenario 4 with the lowest resilience. It also shows the difference in the different connection technologies employed in scenario 5 and scenario 2. Scenario 2 has the highest resilience, but the lowest adaptiveness. Scenario 5 has the highest adaptiveness, but a medium resilience and scenario 4 has a high resilience, but a medium score in terms of adaptiveness.

Although the resilience of the social contribution is not only affected by the number of connections but also by the total generating capacity in the system, it does show some

interesting features of the different evolutionary pathways in the context of infrastructure development. In all three scenarios, the same number of grid connections is used to provide electricity. However, the number of grid connections, sugar mill connections and solar systems differs for each of the different evolutionary pathways. Figure A4-10



figures shows that with the right combination and the right timing of installing minigrids, sugar mills and grids in the right municipalities, a much larger number of municipalities can be electrified than in other cases. However, this problem is very difficult to resolve from an individual perspective. The consequences of the decisions of provinces and the concessionaires are interdependent, although they individually assess the different municipalities they govern and decide accordingly. The interdependency occurs through the way in which their decisions affect the electrification density (# of unelectrified households per km²) in the municipalities. A changed electrification density affects the decision situation of the other organisation in the network and therefore the sequence with which projects occur.

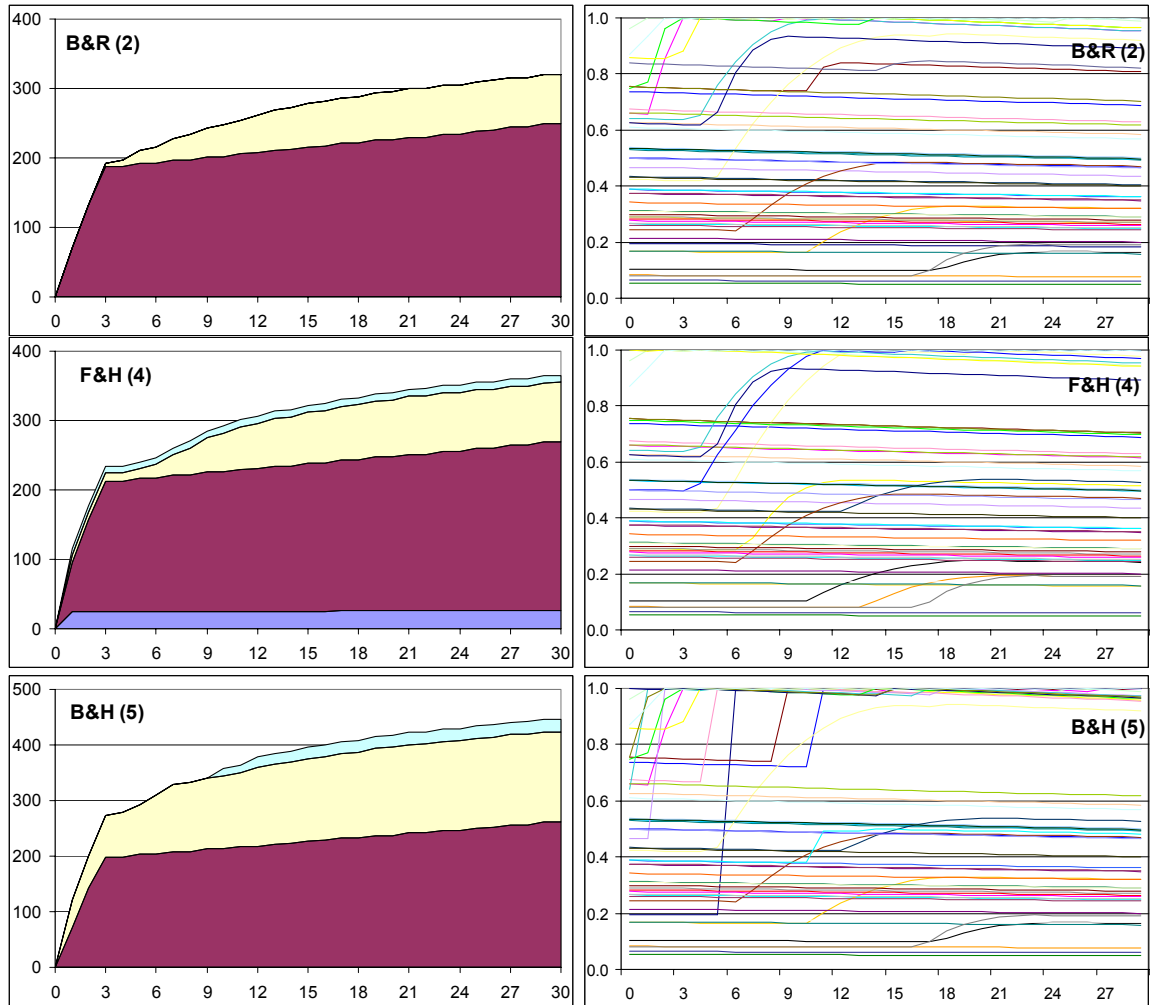
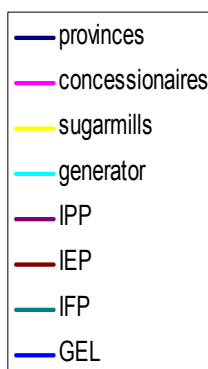


Figure A4- 10 Different structure for electrification and the associated effects on the electrification rates of municipalities

A4.4 Modelling results for sustainable strategic decisions

The need to incorporate sustainable development as an integral part of the strategic decision making process of an organisations receives increasing attention from not only industrial organisations themselves, but also from shareholders and customers. The problem is, however, that the adoption of practices stimulating sustainable development of individual activities not necessarily leads to sustainable development of the system (see for more details the discussion in chapter 4). Although there have been some attempts to develop policies that target sustainable development of total supply chains rather than individual organisations (VROM 2000 see for example), the results are still marginal. Chapter 7 discussed in detail how two different MCDA techniques to integrate environmental and social concerns into the strategic decision making process of an organisation affect the network evolution as a whole. The two MCDA techniques that were explored are Multi-Attribute Utility Theory (MAUT) and the outranking technique ELECTRE III). These two MCDA techniques represent different views on in how far economic, environmental and social criteria can compensate each other. From this perspective, ELECTRE III is viewed as aligned with ‘strong sustainability’, because it sets limits to the degree of compensation between economic, environmental and social performance (Munda 2005).



Chapter 7 illustrated how the different decision making procedures impact the energy production and the number of households that are connected to the electricity grid. Furthermore, it illustrated the difference in economic, environmental and social performance between economic decision making (whereby the value of CO₂ emission reduction is monetarily internalised) and MAUT and ELECTRE III. This section displays the results about the impact on the total CO₂ emission reduction and it provides a comparison of the differences in electrification rates between MAUT and ELECTRE III.

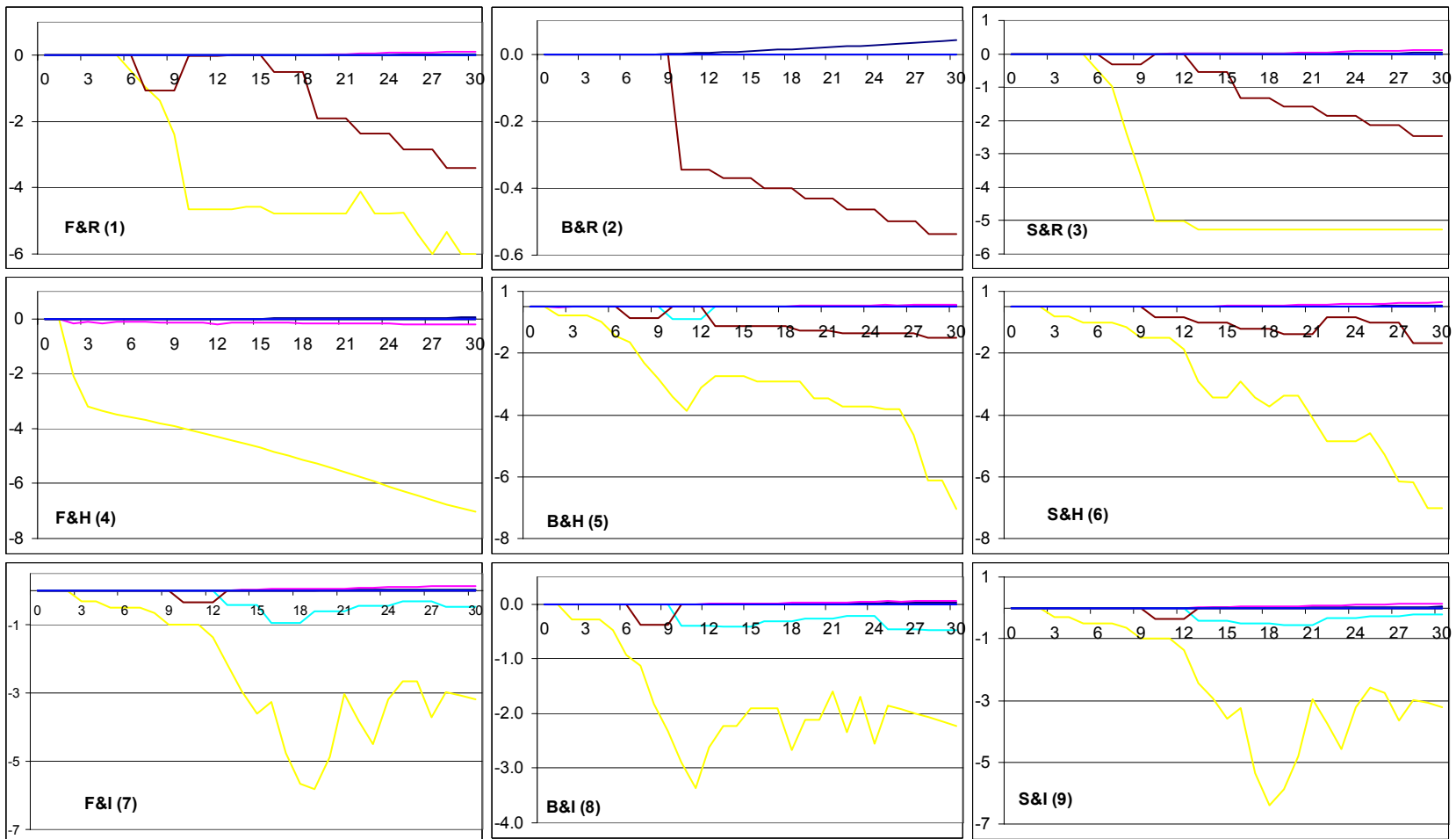


Figure A4- 11 CO₂ emission profiles (in Mtonnes) for the different scenarios when organisations use MAUT for strategic decision making (legend on previous page)

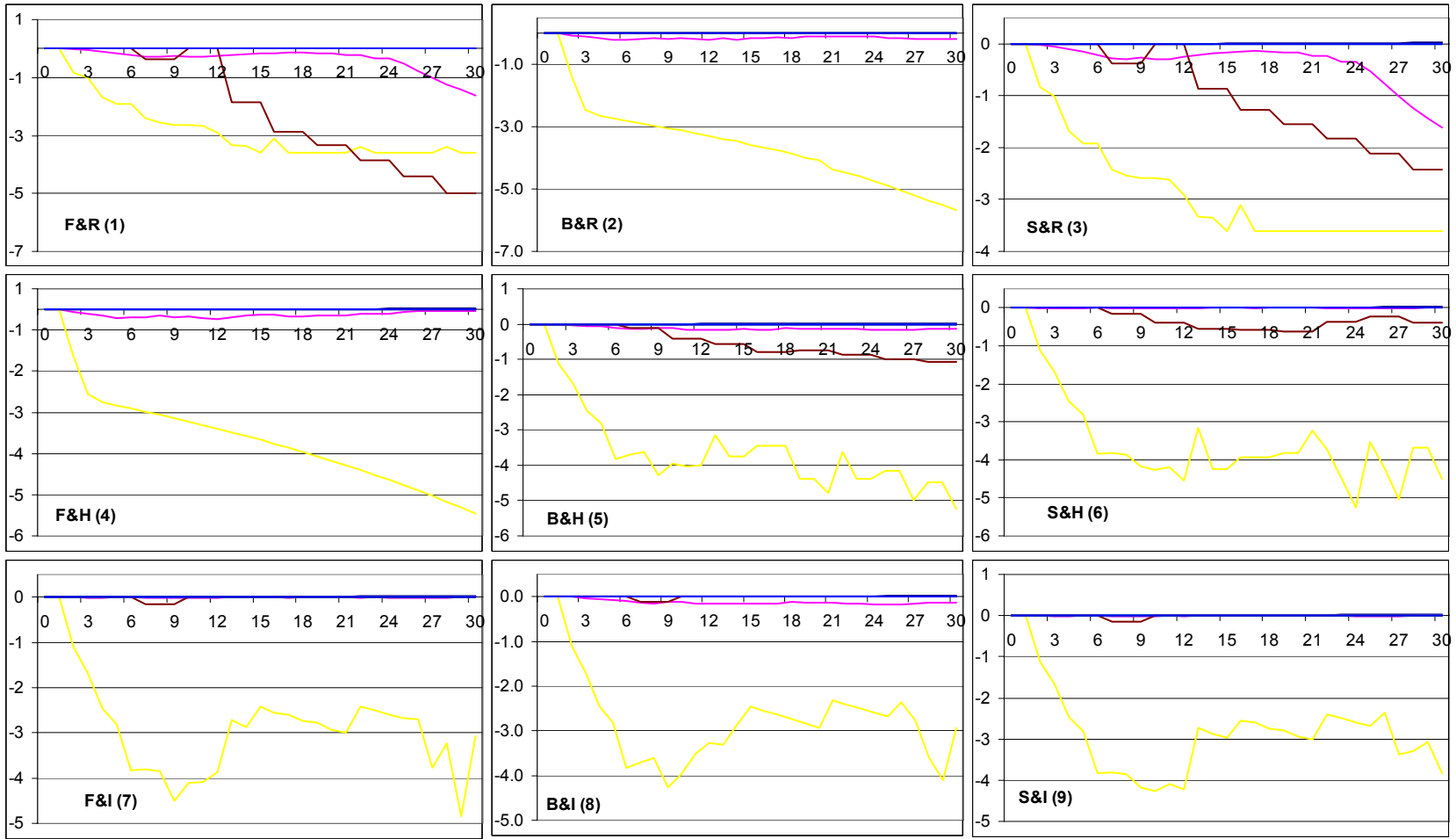


Figure A4- 12 CO₂ emission profiles (in Mtonnes) for the different scenarios when organisations use ELECTRE III for strategic decision making (legend on previous page)

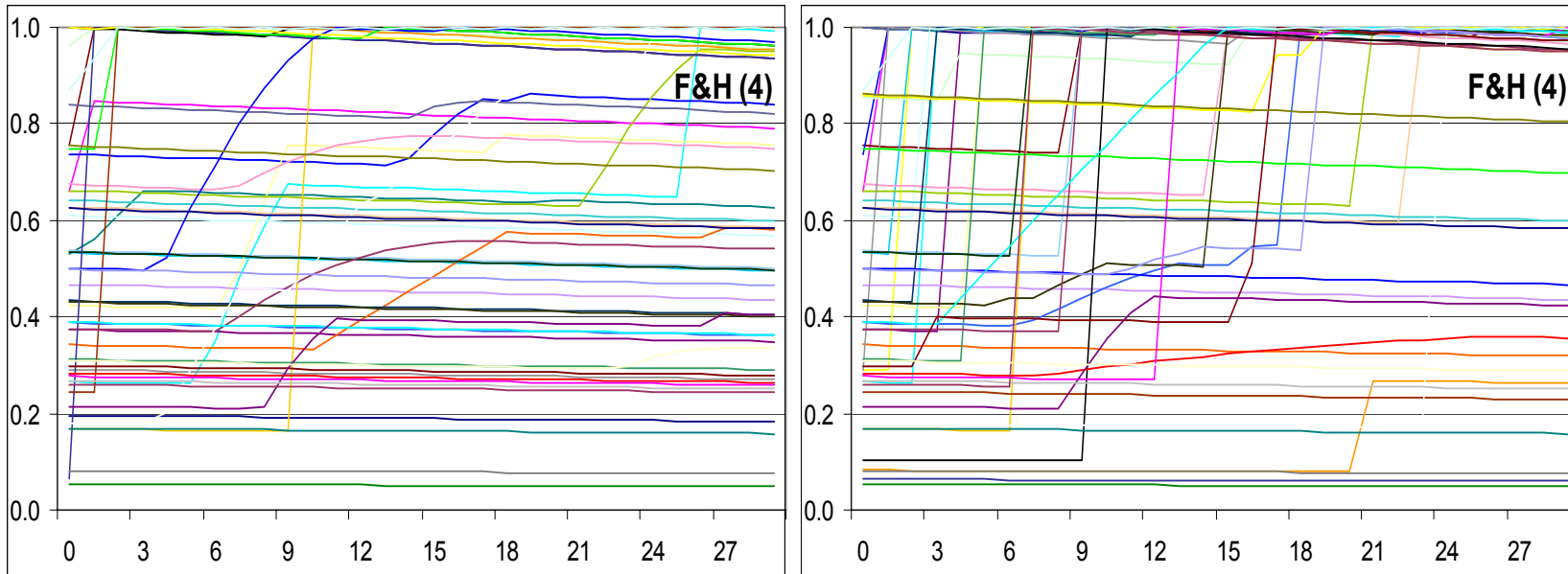


Figure A4- 13 Comparison of the difference in electrification rates in 58 municipalities under MAUT (left) and ELECTRE III (right) in scenario 4

The results in figure A4-11 and A4-12 show that, except for scenario 2, the CO₂ emission profiles become reasonably similar. Most evolutionary pathways are dominated by localised production of electricity, therefore contributing most to the total CO₂ emission reductions throughout the network evolution. Furthermore, the results show that with organisations using ELECTRE III the concessionaires also start to contribute to the emission reduction through the large scale installation of solar systems.

Figure A4-13 shows a comparison between the electrification rates of the 58 municipalities when either MAUT or ELECTRE III is used. The compensatory nature of MAUT and the weight assigned to the social benefit of electrification makes the provinces and concessionaires choose for municipalities with very low electrification rates. This can be seen by the vertical lines of electrification. The non-compensatory nature of ELECTRE III seems to prefer those municipalities that are in the medium range of electrification. Thus, the electrification occurs more in those municipalities that are not too expensive (what leaves out the municipalities with very low density) and those municipalities that provide no social benefits (the municipalities with high density rates). Overall, this strategy provides more municipalities with full electrification than the use of MAUT.

A4.5 Modelling results for government interventions

A second set of interventions that is explored to stimulate sustainable development of bioenergy network are subsidiary and financial instruments by the national government.

The following interventions are explored:

1. The SA government does not develop any policy instruments
2. The SA government install price instruments with a 20% rebate on market prices for electricity. These instruments will be in place until the current green electricity target (10 TWh) is met.
3. The SA government install investments instruments that provide up to 20% off current capital investment costs of new electricity generators. These instruments will be in place until the current green electricity target (10TWh) is met.
4. The SA government sets a higher target for green electricity (10% of total need in region). It uses price instruments that progressively increase and give up to 50% rebate on market prices for electricity to achieve this target.
5. The SA government sets a relative target for green electricity (10 % of total need in region). It uses investment instruments that progressively increase up to 50% rebate on current investment costs for new electricity generators.
6. The SA government reduces the tax rates on profits made from organisations operating in the bioenergy network from 35% (current rate) to 20%.

—	provinces
—	concessionaires
—	sugarmills
—	generator
—	IPP
—	IEP
—	IFP
—	GEL

Chapter 7 already demonstrated the effects of three interventions on the energy production in the different evolutionary pathways. This section provides more illustrations on the effect of the different governmental interventions on the total CO₂ emission reduction and on the number of households that are electrified by the provinces and concessionaires.

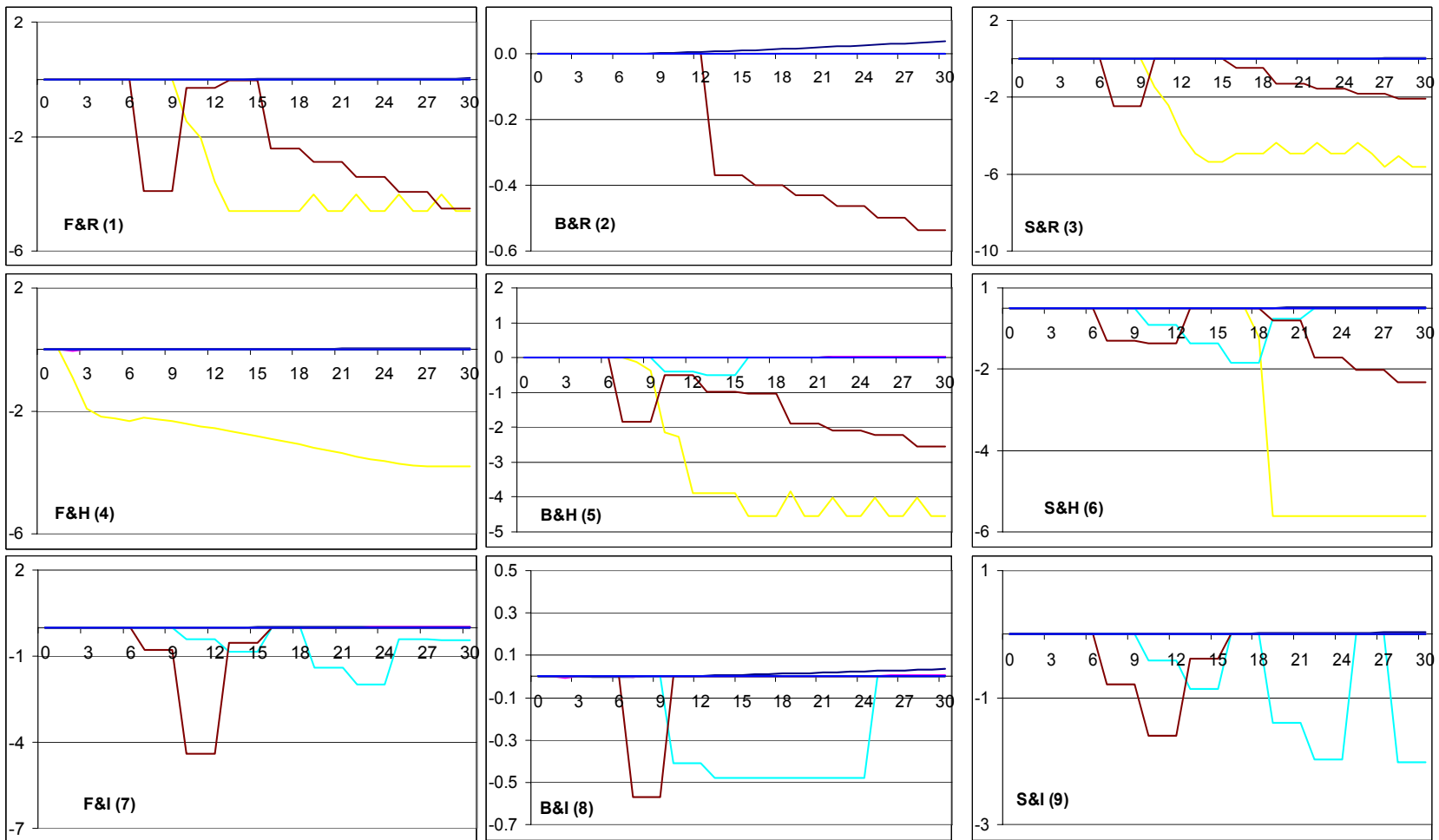


Figure A4- 14 CO₂ emission profiles (in Mtonnes) for the different scenarios when governments introduce price subsidies (legend on previous page)

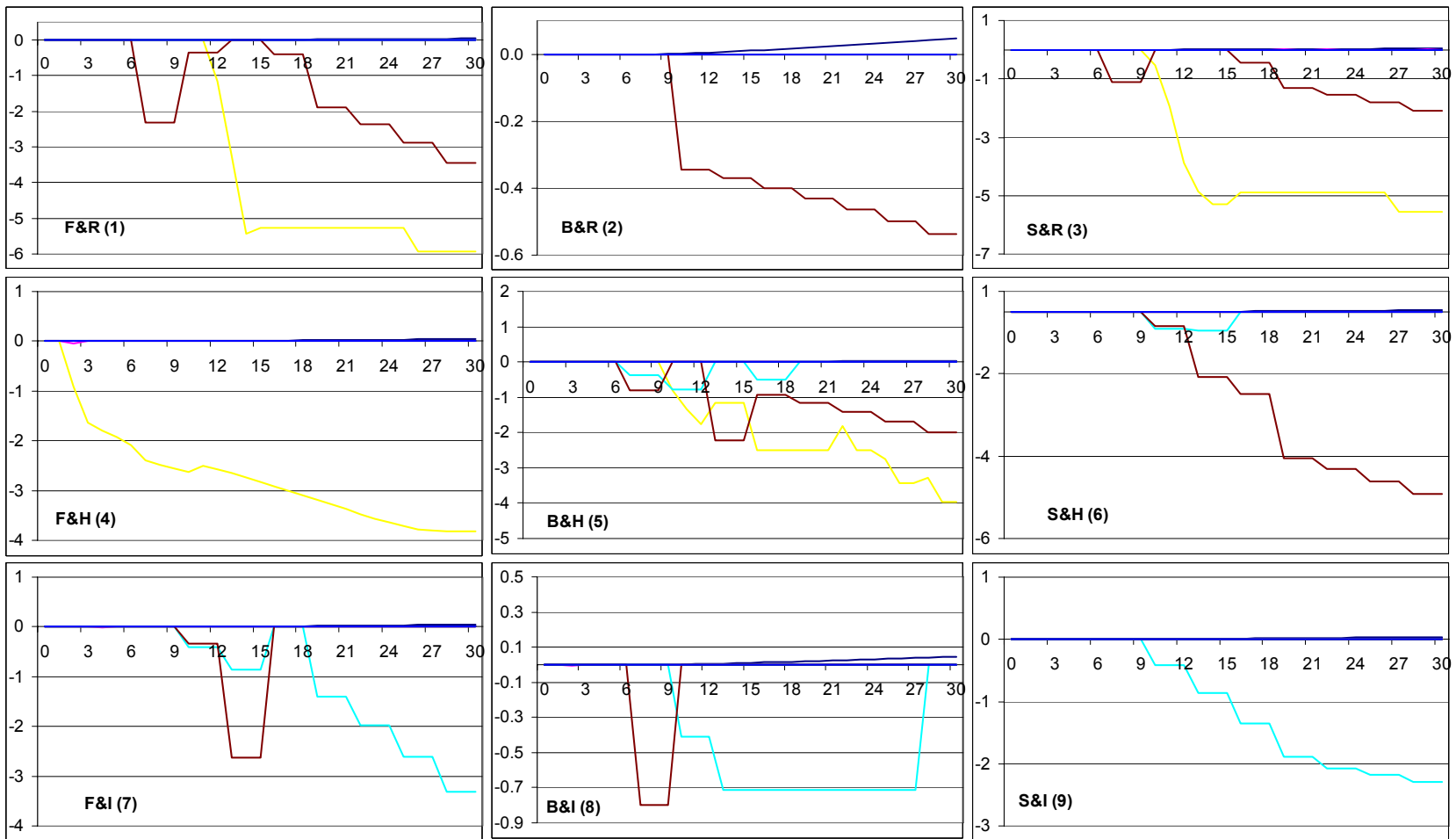


Figure A4- 15 CO₂ emission profiles (in Mtonnes) for the different scenarios when governments introduce investment subsidies (legend on previous pag)

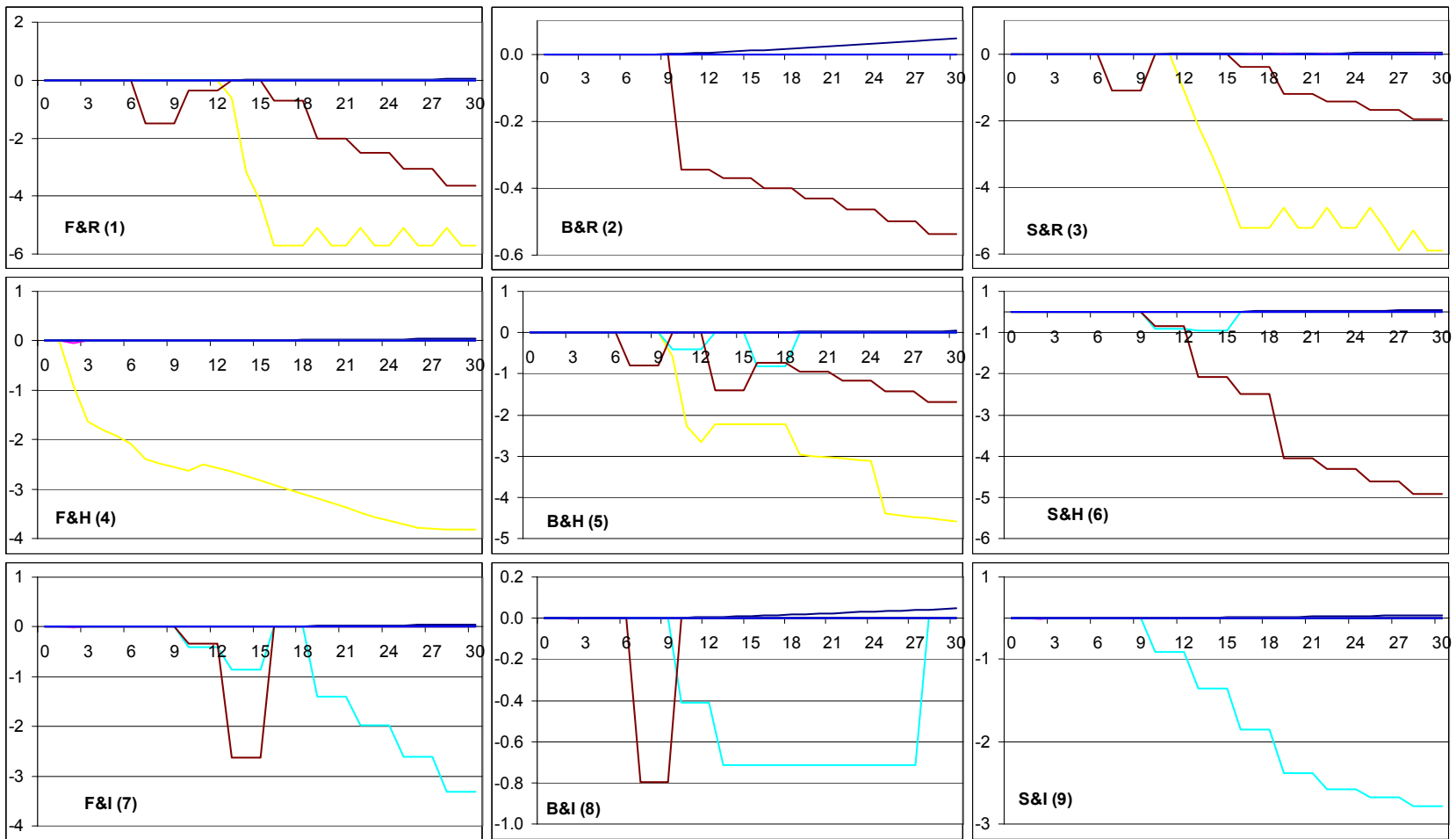


Figure A4- 16 CO₂ emission profiles (in Mtonnes) for the different scenarios when governments introduce tax reductions (legend on previous page)

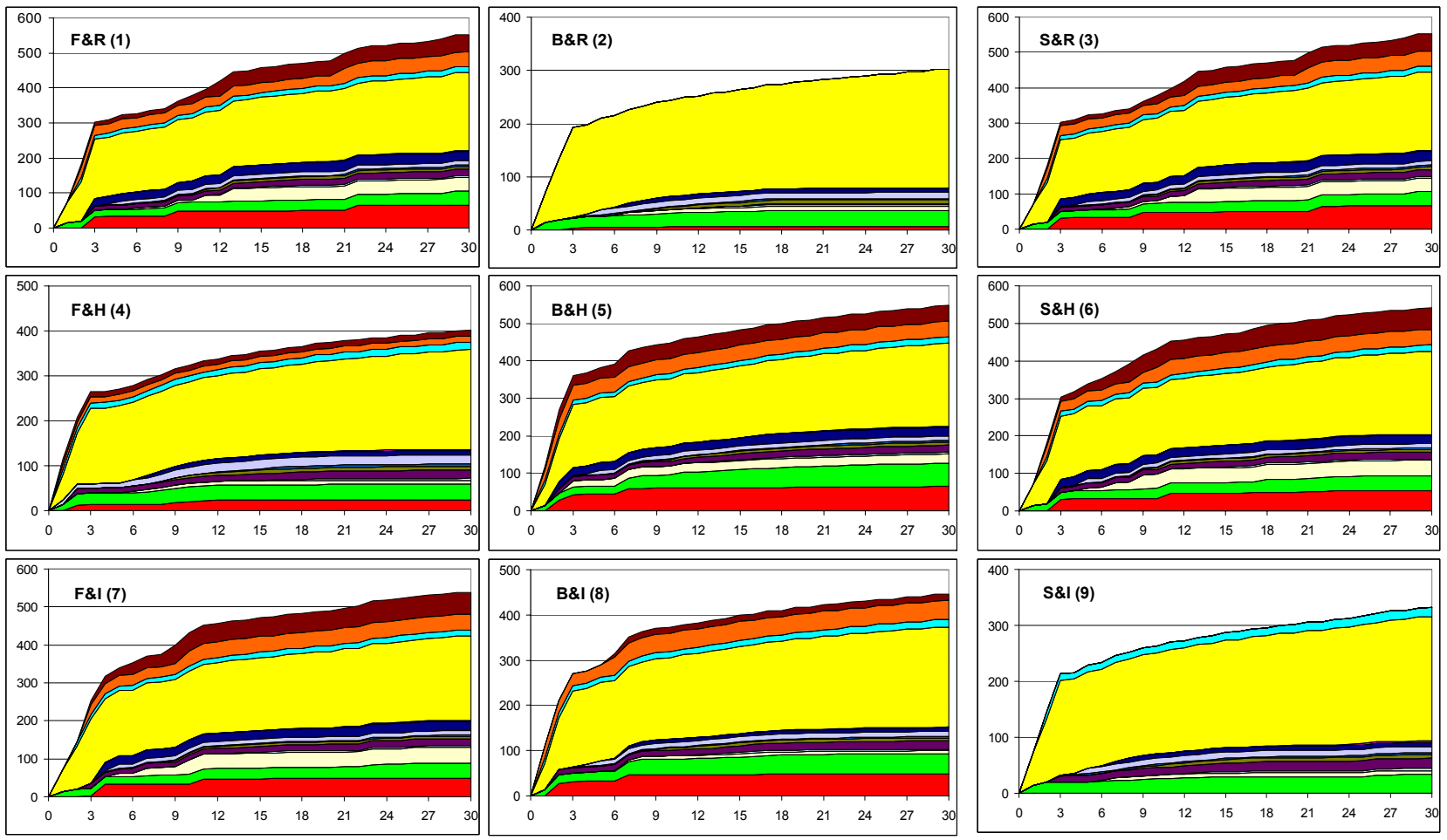


Figure A4- 17 Number of household connections (x 1000) by local governments and concessionaires for the different scenarios when governments introduce price subsidies (legend on next page)

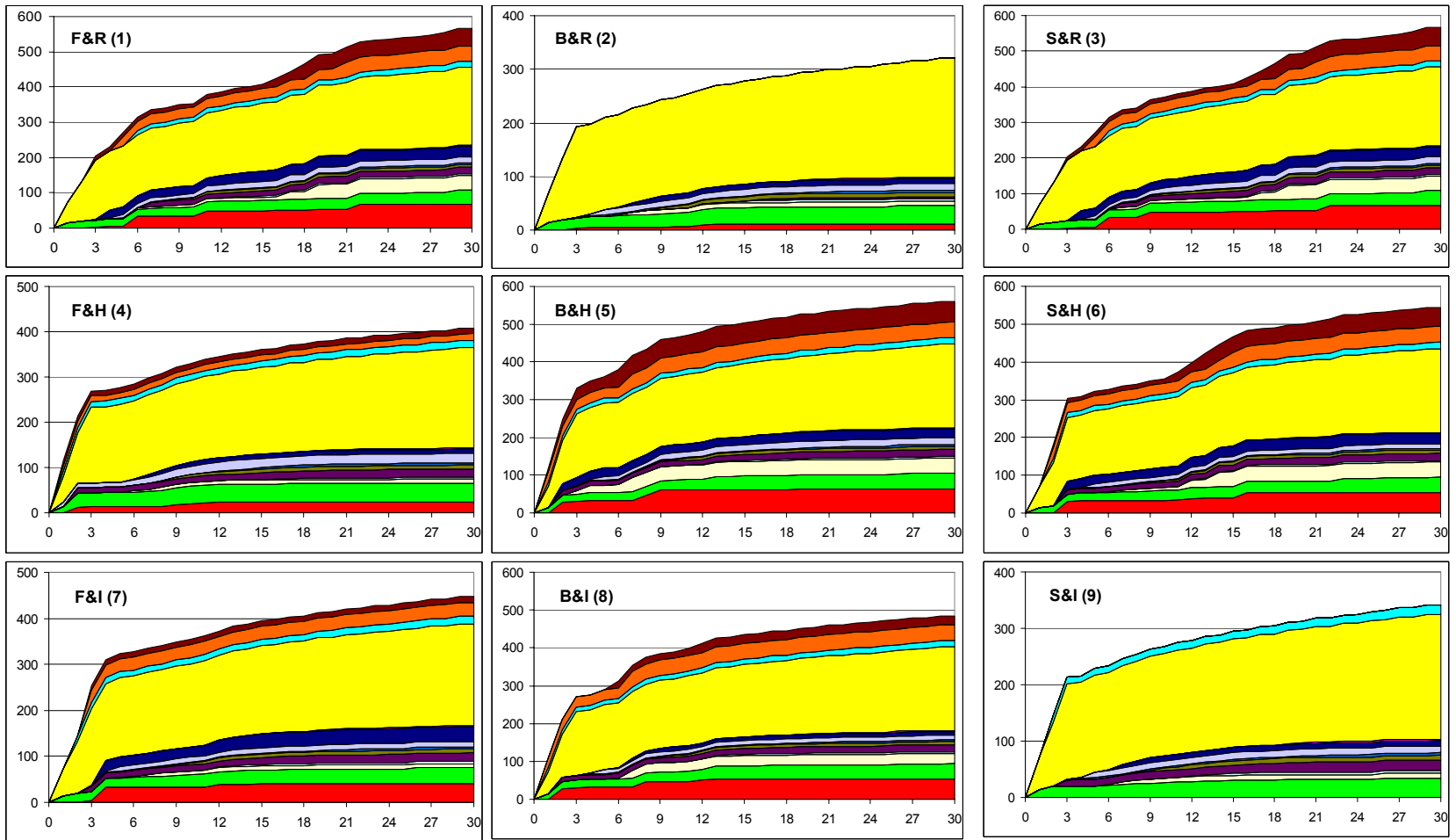


Figure A4- 18 Number of household connections (x 1000) by local governments and concessionaires for the different scenarios when governments introduce investment subsidies (legend on next page)

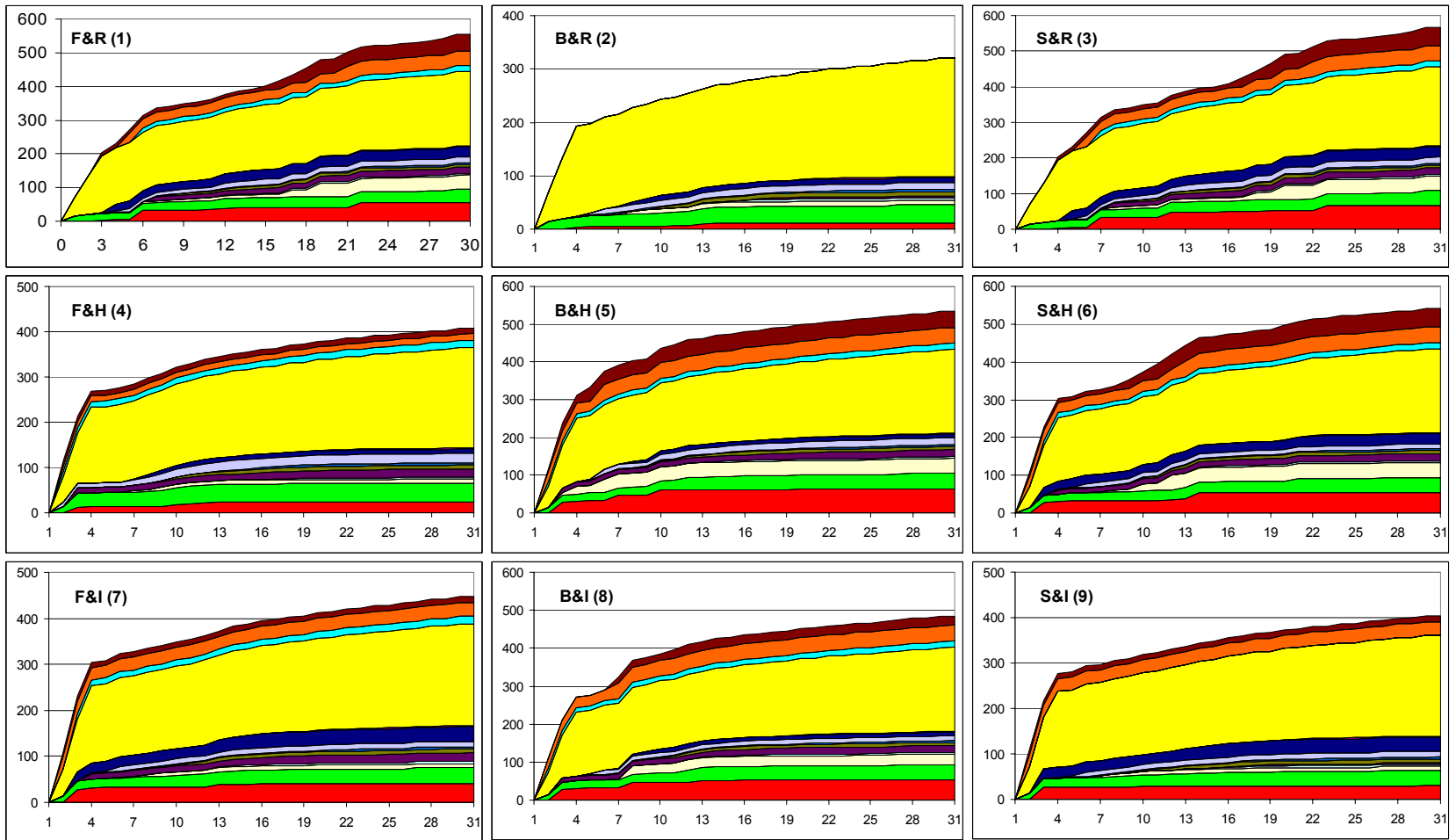


Figure A4- 19 Number of household connections (x 1000) by local governments and concessionaires for the different scenarios when governments introduce tax reductions (legend on next page)

- Edf
- Shell
- Nuon
- Ethekwini
- Sisonke
- Ilembe
- Uthungulu
- Umkhanyakude
- Zululand
- Amajuba
- Umzinyathi
- Uthukela
- Umgungundlovu
- Ugu

The results confirm that the findings presented in chapter 7 that government interventions have limited effect on the network evolution and that there are only selected scenarios (most notably scenario 2 and 6) in which the evolution changes. Furthermore, the results show that government interventions can have both positive and negative consequences for the network evolution. For example, in scenario 6 both investment subsidies and tax reductions limit the opportunity for localised production of electricity by the sugar mills, because they receive competition from an independent ethanol producer in the early stages of the network. This limits the opportunity for minigrids connected to sugar mills. Similarly, investment subsidies and tax reductions limit the opportunity for the independent power producer to enter the network, because it becomes more

profitable to use the bagasse for cofiring.

In terms of infrastructure developments, there are hardly any differences in the network evolutions. In principle, concessionaires should benefit from any of the three government incentives. Price subsidies increase their returns on the production of green electricity, investment subsidies reduce the capital costs for investments in minigrids and solar systems and the tax revenues increase the overall profitability of their ventures. However, in none of the scenarios there is a substantial increase in the number of household connections that are connected to electricity via concessionaires (except in scenario 9 under tax reductions). These results seem to suggest that the governmental interventions explored within this thesis are not effective in increasing the electrification rate in KwaZulu-Natal.

A4.6 Combing agent-based modelling with global dynamic optimisations

In the evaluation of sustainable development in the bioenergy case study, the performance scores have been based on a relative comparison of the different scenarios and/or interventions that have been explored. This means that the results of these evaluations can only be used to compare the different interventions to each other and not with regard to their contribution for achieving a particular sustainability goal. Section 4.5.1. suggested the use of agent-based modelling combined with global dynamic optimisation models (GDOM) to provide an external reference point to compare the different interventions with. The use of this combined approach of global dynamic optimisation modelling and agent-based modelling has been described in two publications associated with this thesis (Beck, Kempener et al. 2008; Kempener, Beck et al. in review). This section provides a short overview of the results of Kempener, Beck et al., which is based on the same bioenergy case study model as explored in this thesis.

A.4.6.1 Agent-based modelling and GDOM

Firstly, a set of standard scenarios have been developed to evaluate the potential contribution of different evolutionary pathways towards economic, environmental and social performance criteria. In this case, two scenarios have been used. The first scenario represents a network where all organisations use an IRR-threshold of 15% to determine the economic viability of their investment decisions. Furthermore, they base their decisions about exchange potential exchange partners on the basis of price. This scenario is referred to as the 'economic rational' scenario. Scenario B is based on organisations using Multi-Attribute Utility Theory (MAUT). In this scenario, organisations also use an IRR-threshold of 15% to evaluate potential investments in technologies. However, in scenario B organisations are willing to trade off the IRR-threshold to compensate for positive social and environmental impacts. In other words, they are willing to reduce their IRR-threshold if the decision has positive impacts either socially and/ or environmentally. The willingness to trade-off the IRR-threshold to social and/or environmental considerations is set at 33%, meaning that each objective is equally important.

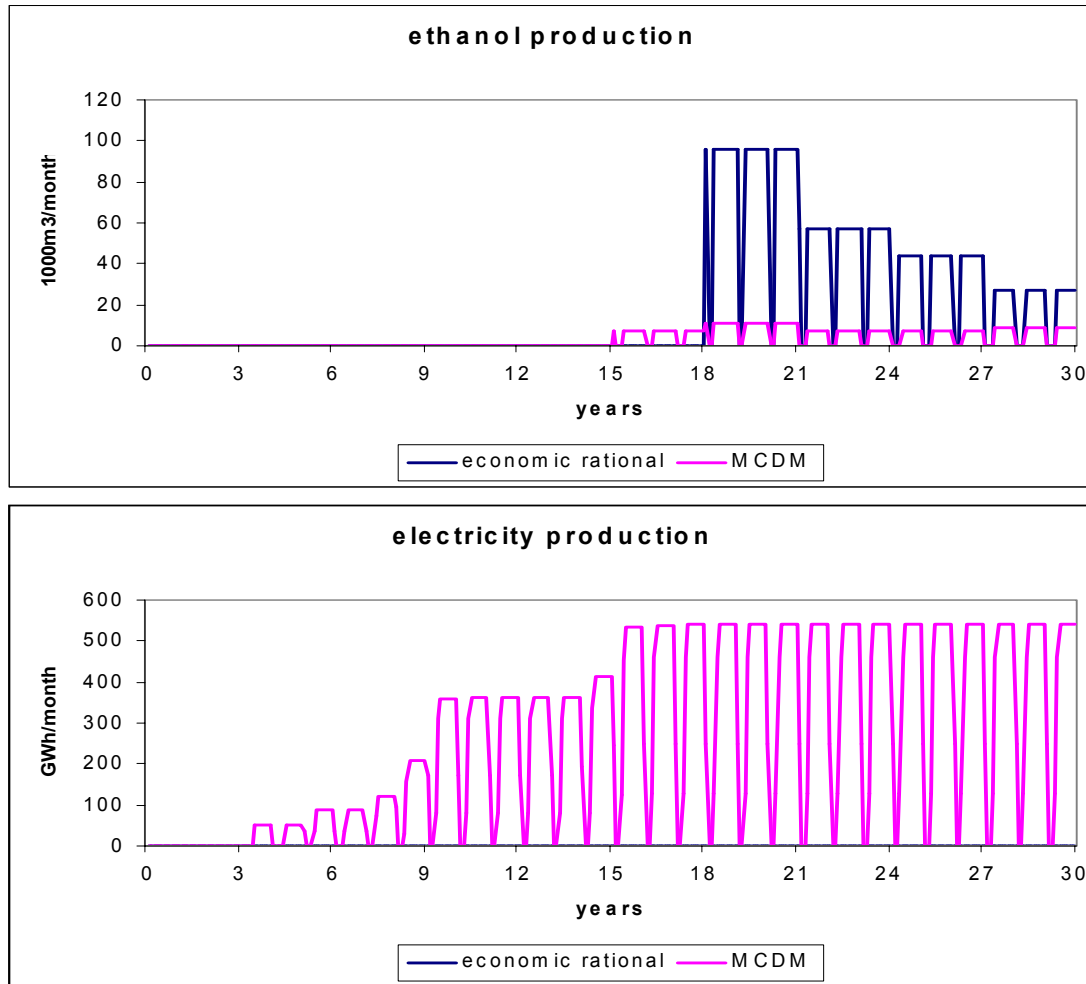


Figure A4- 20 The effects of economic rational versus multi-criteria decision making on the electricity and ethanol production (Kempener, Beck et al. in review)

Figure A4-20 shows the different profiles for electricity and ethanol production for the two scenarios. No electricity is produced by economically rational agent and a large capacity for ethanol production is built in year 18. Once again, the saw-tooth profiles are indicative of investment patterns which mirror the growing cycle of bagasse i.e. no dried and pelletised product is made. The sugar mills are much more willing to start producing electricity locally on the basis of wet bagasse, thereby contributing to CO₂ aversion and the rural development of local municipalities. However, the economic consideration does play a role as the sugar mills do not upgrade or expand their electricity generation capacities with increasing bagasse availability, but rather sell the bagasse to a centralised ethanol producer. The overall effect is a striking increase in the amount of energy supplied to local communities (see Table 4). As expected, the environmental and

social performance of a network with agents using multiple objectives is significantly better than one in which agents behave entirely rational from an economic perspective alone. However, the economic performance is roughly half. Of course, there is little real significance which can be attached to this network-wide economic indicator. It serves only to suggest that the system as a whole is profitable (which would presumably be of interest to government ministries in terms of tax revenues and such), but says nothing about the profitability of any of the individual agents in the network.

Table A4- 1 Comparison of network performance (Kempener, Beck et al. in review)

	economic	environmental	social	energy provision
	(billion ZAR)	(Mt CO2 averted)	(rural energy supply)	(PJ)
Economically rational agents	6.6	36.9	1.1	121.7
Agents who allow MCDM	3.4	186.9	16.0	355.8

A4.6.2 Global Dynamic Optimisation Results

Not surprisingly, results of the GDOM differ in many respects from those of the ABM. Here the focus is on “system wide” performance indicators over the entire time horizon (30 years). Table A4-2 is the analog of Table A4-1. Comparing these two tables, it is evident that the agent-based models do not generate networks whose overall performance matches that of the global dynamic optimisation. Thus it might be argued that agent-behaviour impedes potential network performance in terms of the stated objectives. This is examined in further detail in section A4.6.3.

Table A4- 2 Dynamically Optimal Network Performance (Kempener, Beck et al. in review)

	economic	environmental	social	energy provision
	(billion rand)	(Mtonnes co2 averted)	(rural energy supply)	(PJ)
Environmental behaviour	0.2	308.3	0	637
Social behaviour	-59.3	102.2	415.8	1219
Economic rational	12.7	226.6	0	913

A4.6.3 Comparison between agent-based results and global dynamic optimisation

In order to provide insights for the development of government policies and/or business strategies, a framework is required in order to assess the overall performance of the different scenarios in the agent-based models. Without such a reference framework, it is impossible to tell whether the developed government policies and/or business strategies will contribute to the desired outcome.

The dual approach of developing global dynamic optimisation models together with agent-based models provides a means to compare the effectiveness of government policies towards multiple objectives. With the functional unit of our analysis defined as the additional energy provision through the use of bagasse, the three objectives considered in this study are:

1. economic performance: yearly annualised capital costs and revenues discounted over the life time (30 years) of the analysis.
2. environmental performance: the total CO₂ emissions averted
3. social performance: the fraction of electricity and thermal energy to meet needs in rural areas .

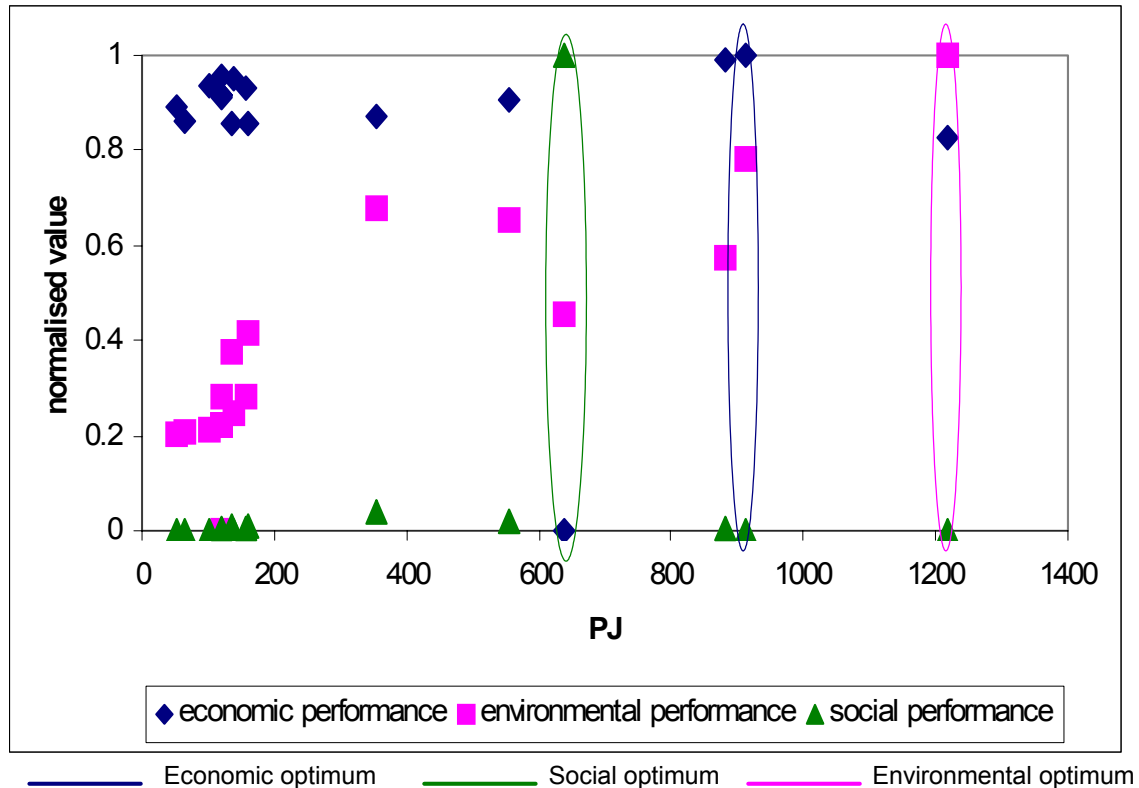


Figure A4- 21 Comparison of GDOM and ABM results for selected parameter values (Kempener, Beck et al. in review)

Figure A4-21 shows a comparison of the ABM global performance results with the GDOM configurations for economic, social and environmental performance and their associated scores in the other performance criteria.

Several specific observations can be drawn from this comparison:

1. The energy output of the optimal network configurations is in general higher than from the agent-based models. One of the main reasons for this is that the network configurations in the GDOM use bagasse as an energy source over the whole analysis period, while in most agent-based models, investments occur only after about 15 years.
2. Secondly, in most agent-based models the production of ethanol becomes more profitable than electricity production.
3. Most agent-based modelling results are relatively similar, except for three network evolutions. The three network evolutions with higher energy outputs and

higher associated environmental and economic performances occur under the following circumstances:

- a. A high green electricity subsidy of 60%
- b. Agents using MCDM
- c. Agents using a low IRR-threshold of 5%.

These three evolutions are similar in that they all accommodate pelletising of bagasse and energy production in the existing power station, over the initial bidding cycles. This stage is followed up by local production of electricity and ethanol production in the final years of the analysis.

4. The economic performance of the agent-based models seems to be approaching the global optimum performance. However, this performance score is rationed against “best” and “worst” scores achieved under the GDOM. In this latter case, socially optimal models have negative NPVs, which skews the results from the ABMs, making them appear more favourable than they are in practice.
5. The GDOM optimal social performance is much higher than that of any of the other ABM runs. From an economically rational perspective, the ABM delivers a low social score in the main.
6. The second highest social score is achieved by agents using MCDM (in which social concerns are given an elevated weighting).
7. From an economically rational perspective, the ABM delivers a low social score in the main.

The general pattern from the GDOM is as follows: The optimal social performance occurs through the provision of gel-fuel to rural areas as the need for cooking and heating is higher than the need for electricity. However, the associated economic performance is very poor. The best economic performance can be achieved through the provision of electricity on the basis of wet bagasse. Although this configuration results in lower electricity output through lower efficiencies and higher emissions through increased transport, it does reduce the capital costs associated with pelletising. The best environmental performance can be achieved through pelletising of bagasse, which slightly increases the capital costs.

From the perspective of the ABMs, there are two distinct differently network configurations and energy outputs. The networks with low energy output typically

produce ethanol. Furthermore, a positive correlation can be seen between increased energy output and environmental performance, due to the direct correlation between bioenergy and the aversion of CO₂ associated with the use of fossil fuel sources. Thirdly, it should be noted that the social performance of the agent-based models is very poor in comparison the global optima. The main reason for this is the rural electrification policy in place in South Africa. Currently, local government allocates an annual budget to provide electricity connections to rural areas. The cost of grid connections is much higher than localised production of electricity through sugar mills and distribution of this electricity through mini-grids. However, local government only decides to allocate electrification grants to the establishment of mini-grids *after* sugar mills have decided to produce electricity locally. There is thus a large time lag between the localised production of electricity and government's ability to provide electricity through mini-grids. This points to the key role of non-industrial agents in the development of such networks.

A4.7 References

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