A HOLISTIC APPROACH TO SUSTAINABILITY ANALYSIS OF INDUSTRIAL NETWORKS

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March 2008

DECLARATION

I, Jessica Beck, herewith declare that this thesis is entirely the result of my own work unless otherwise indicated.

J. Beck

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Date

EXECUTIVE SUMMARY

The aim of this thesis is to support the evaluation of sustainable development strategies for industrial networks in the context of industrial ecology (IE). Industrial networks are a group of units which carry out, or contribute to, industrial activity, and are connected by material and energy flows, but also capital and information exchanges. The components of an industrial network encompass resource extraction, processing and refining, forming and assembly, use, disposal, as well as recycling and reprocessing. The motivation behind this research is the realisation that much of the current environmental system analysis focus within IE lacks a structured approach to considering:

- system environment
- dynamic nature of the system and its environment
- economic and social impacts
- the effect of uncertainty on analysis outcomes.

It is argued in this thesis that current environmental analysis approaches used in IE can be improved in their capacity to capture the complexity of industrial systems, with the objective of promoting sustainable development. While IE emphasises the benefit of a systems approach to identifying environmental strategies in industry, analysis tools have to date not engaged extensively with important aspects such as the influence of system environment and dynamics on the viability of an environmental strategy, or with the economic or social impacts of industrial system development, which are equally important for sustainable development. Nor is the assessment of the effect of uncertainty on analysis outcomes an integral part of environmental analysis tools in IE. This is particularly significant when, in fact, the degree of uncertainty in assumptions and data used increases with the scope, and therefore the abstraction, of the system under consideration.

IE will have to engage with the network and contextual complexities to a greater degree if it is to evolve from a concept to the application of its principles in practice. The main contribution of this thesis is therefore the development of a structured approach to analysing industrial networks for the purpose of identifying strategies to encourage sustainable development, while accounting for the complexity of the underlying system as well as the problem context. This analysis is intended to allow the identification of preferred network development pathways and to test the effectiveness of sustainable development strategies. A top-down, prescriptive approach is adopted for this purpose. This approach is chosen as the industrial network analysis is intended to identify how a network *should* develop, rather than focusing on how it could develop.

Industrial networks are systems which are complex in both their structure and behaviour. This thesis also delivers a characterisation of these networks, which serves two purposes – quantifying key elements of structure and behaviour; and using this information to build a foundation for subsequent industrial network analysis. The value of such an approach can be seen in the following example. With a detailed understanding of individual network characteristics, both separately and collectively, it is possible to determine the source of issues, the means available to address them, any barriers that might exist, and the consequences of implementing any strategic interventions.

The analysis approach proposed in this thesis is based on multi-criteria decisions analysis (MCDA), which, as a process, combines initial problem structuring and subsequent quantitative analysis stages. The tools employed within MCDA have been employed variously around considerations of sustainable development. Their value in this thesis is their integration within a rigorous analytical framework. Rigorous problem structuring is attractive as it helps elucidate the complexities of the system and its environment and is, by definition, designed to deal with multiple environmental social and economic criteria that would have to be considered to promote sustainable development. For the quantitative analysis, the industrial network analysis draws from existing analysis tools in IE, but predominately from other systems research disciplines, such as process systems engineering (PSE) and supply chain management (SCM). These fields, due to their maturity and practical focus, have invested a lot of research into system design and strategic planning, capturing system dynamics and uncertainty to ensure, within selected system constraints, that a proposed system or changes to a system are viable, and that the system is capable of achieving the stated objectives. Both PSE and SCM rely heavily on optimisation for system design and planning, and achieve good results with it as an analytical tool. The similarity between industrial networks and process systems / supply chains, suggests that an optimisation platform, specifically multi-objective dynamic optimisation, could be employed fruitfully for the analysis of industrial networks. This is the approach taken in this thesis. It is consistent with the “top down” approach advocated previously, which is deemed preferable for the identification and implementation analysis of strategic interventions. This enables the determination of a structure (design) that is “best” able to operate under future conditions (planning) with respect to the chosen sustainable development objectives.

However, an analysis is only ever as good as its underlying data and assumptions. The complexity and scope of the industrial network and the challenge of articulating sustainable development target(s) give rise to significant uncertainties. For this reason a framework is developed within this thesis that integrates uncertainty analysis into the overall approach, to obtain insight into the robustness of the analysis results. Quantifying all the uncertainties in an industrial network model can be a daunting task for a modeller, and a decision-maker can be confused by modelling results. Means are therefore suggested to reduce the set of uncertainties that have to be engaged with, by identifying those which impact critically on model outcomes. However, even if uncertainty cannot be reduced, and the implementation of any strategy retains a degree of risk, the uncertainty analysis has the benefit that it forces an analyst to engage in more detail with the network in question, and to be more critical of the underlying assumptions.

The analysis approach is applied to two case studies in this thesis: one deals with waste avoidance in an existing wood-products network in a large urban metropolis; the other with the potential for renewable energy generation in a developing economy. Together, these case studies provide a rich tableau within which to demonstrate the full features of the industrial network analysis. These case studies highlight how the context within which the relevant industrial network functions influences greatly the evolution of the network over time; how uncertainty is managed; and what strategies are preferred in each case in order to enhance the contribution of each network to sustainable development.

This thesis makes an intellectual contribution in the following areas:

- the characterisation of industrial networks to highlight sources of environmental issues, role the characteristics (could) play in the identification of (preferred) sustainable development strategies, and the need to explicitly consider these in a systems analysis.
- the synthesis, adaptation and application of existing tools to fulfil the need for analysis tools in IE that can handle both contextual and system complexity, and address the above mentioned issues of lacking consideration of
  - system environment
  - dynamic nature of the system and its environment
  - economic and social impacts
  - the effect of uncertainty on analysis outcomes.
- the development and demonstration of an industrial network analysis approach that
  - is flexible enough to model any industrial network at the inter-firm level, regardless of form and configuration of materials and products circulated, and depending on the existing network and the proposed strategies.
  - is able to encompass a wide range of environmental strategies, either individually or in combination depending on what best suits the situation, rather than focusing on any strategy in particular.
  - ensures long term viability of strategies, rather than short term solutions delivering incremental improvement.
- the development of a comprehensive approach to capturing and assessing the effect of uncertainty on solution robustness for industrial network analysis, including the screening to determine the most important parameters, considering valuation and technical uncertainties, including future uncertainty.

The industrial network analysis approach presented in this thesis looks more to how a network should develop (according to a set of sustainable development objectives), rather than how it may in actual fact develop. Consequently, the influence of agent interests and behaviour is not considered explicitly. This may be construed as a limitation of the industrial analysis approach. However, it is argued that the "top down" modelling approach favoured here is useful at a policy-making level. Here, for example, government instrumentalities, trade organisations and industry groupings, non-government organisations and community-based organisations are likely to be interested more in the performance of the network as a whole, rather than (necessarily) following the behaviour of individual agents within the network. Future work could well entertain the prospect of a mixed approach, in which the top-down approach of this thesis is complemented by a "bottom-up", agent-based analysis. In this manner, it would be possible to give an indication of how attainable the identified industrial network development pathways are. Furthermore, the use of government incentives can be explored to assess if network development could approach the preferred development pathway which is identified using the methodology and results articulated in this thesis.

The following papers and presentations have resulted from this research:

Publications

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LIST OF ACRONYMS

ABBREVIATION	MEANING
AMPL	Another Mathematical Programming Language
AUD	Australian Dollar
BCSD	Business Council for Sustainable Development
BEE	Black Economic Empowerment
BIG/GT-CC	Biomass Integrated Gasifier/Gas Turbine-Combined Cycle)
CBA	Cost-Benefit Analysis
CDM	Clean Development Mechanism
CEA	Cost-effectiveness Analysis
CERA	Cumulative Energy Requirements Analysis
DfE	Design for Environment
DME	South African Department of Minerals and Energy
EIA	Environmental Impact Assessment
env. IOA or I/O	Environmental Input-Output Analysis
EIP	Eco-industrial park
EOL	End of Life-Management
EPR	Extended Producer Responsibility
ERA	Environmental Risk Assessment
EV	Expected Value
EVPI	Expected Value of Perfect Information
FFD	Fractional Factorial Design
GAMS	General Algebraic Modelling System
GPI	Genuine Progress Indicator
HRSG	Heat Recovery Steam Generator
IE	Industrial Ecology
IISD	International Institute Sustainable Development
IGCC	Integrated Gasification Combined Cycle
IM	Industrial Metabolism
IPP	Independent Power Producer
ISO	International Standards Organization
KZN	KwaZulu Natal
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCM	Life Cycle Management
LP	Linear Programming

ABBREVIATION	MEANING
MCA	Multi Criteria Analysis
MCDA	Multi Criteria Decision Analysis
MCS	Monte Carlo Simulation
MFA	Material Flow Analysis/Accounting
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MIPS	Material Input per Unit of Service
MOO	Multiobjective Optimisation
NECC	National Electrification Co-ordination Committee
NEP	National Electrification Programme
NER	National Energy Regulator (South Africa)
NGO	Non-governmental Organisation
NLP	Nonlinear programming
NPV	Net Present Value
NSW	New South Wales (Australia)
OR	Operations Research
PCA	Principle Component Analysis
PE	Partial Equilibrium (Model)
PSE	Process systems engineering
RDP	Reconstruction and Development Programme
RE	Renewable Energy
SA	South Africa
SASA	Sugar Association of South Africa
SCM	Supply Chain Management
SETAC	Society of Environmental Toxicology and Chemistry
SFA	Substance Flow Analysis
SMA	Sydney Metropolitan Area
TCA	Total Cost Accounting
TNS	The Natural Step
UNEP	United Nations Environment Program
UOA	Units of Analysis
USD	United States Dollar
VOC	Volatile Organic Compound
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
ZAR	South African Rand

1

INTRODUCTION

1.1 SUSTAINABLE DEVELOPMENT AND INDUSTRY

Industry supports society by providing it with commodities and products catering for needs and wants, as well as employment and prosperity. In doing so, industry contributes significantly to environmental degradation as a result of resource extraction, processing of materials, distribution and use of products, and post-use disposal. The manner and rate at which resources are extracted from and waste is returned to the natural environment are regarded as unsustainable (UN, 2002b). This issue is set to become more critical, as the current intensity of resource use and consumption is unlikely to slow in the foreseeable future. Global population is projected to reach between 7.7 and 10.6 billion by 2050 (United Nations Population Division, Retrieved 16 Dec 2005) while at the same time developing countries strive to attain the same resource intensive standard of living as countries with developed economies.

There is little indication that consumers in future will buy less and use what they buy for longer, as the "*consumer class is growing both in extent and in affluence*" (Hertwich, 2005a). Therefore quality of life of future generations will depend in part on industry finding a balance between satisfying demand for goods and services while at the same time mitigating its impact on the environment. Is it up to industry to find this balance, or government regulation to help drive industry in this direction, and industry to find a way of meeting regulation requirements. "*Industry … is the main productive interface between society and the* *environment, it is the immediate cause of most risks, and, paradoxically, it has the potential to help or hinder the achievement of sustainable development*" (Howes, 2005). There is therefore a need for the generation and implementation of strategies to set industry on the course of sustainable development. Sustainable development in this case is seen to be industrial development that in the first instance manages to mitigate impacts to the threatened natural environment, while maintaining or even improving social and economic development. The term "strategies" in this case refers to one or a number of interventions undertaken in an attempt to improve industrial performance over the long-term.

1.2 INDUSTRIAL ECOLOGY: A SYSTEMS APPROACH TO SUSTAINABLE DEVELOPMENT IN INDUSTRY

Industrial ecology (IE) is based on the premise that industrial systems should mimic natural ecosystems in their material and energy efficiency in order to drive industry towards environmentally sustainable development (Graedel, 1996). In other words waste generation and the consumption of scarce resources should be minimized, as should energy requirements. Industrial wastes and discarded products should be used as input to industrial processes *"...in a way analogous to the cycling of nutrients by various organisms in an ecological foodweb"* (Frosch and Gallopoulos, 1989). Graedel and Allenby (2003) give the following definition for industrial ecology (p. 18):

> *"Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital"*.

The IE approach is a systemic one, which attempts to identify opportunities to promote sustainable development by viewing industrial systems holistically, i.e. as systems that interact with other technological and economic systems, but also form an interface between nature and society (Hermansen, 2006). To explore the potential of promoting environmental sustainable development in industrial systems, IE draws on a variety of environmental frameworks and tools. These range from concepts such as dematerialisation and cleaner production, to procedural tools such as eco-design, to analytical tools, such as material flow analysis and life-cycle assessment (Wrisberg and Udo de Haes, 2002). Existing analysis tools can be classified according to the system type they cover (e.g. symbiosis/geographical system or metabolism/product-based chain (Korhonen, 2002; Seager and Theis, 2002)), the strategy they recommend (e.g. dematerialisation, recycling), or at which level of detail the system is analysed (e.g. intra-firm, inter-firm or the regional/global perspective (Chertow, 2000)). Together, these tools can be seen to form a comprehensive attempt to capture industry activity and its environmental sustainability issues. However, it will be argued here that, individually, these approaches are limited in their view of the system and the issues they address.

The limitations of current tools can be attributed to the fact that IE is still a relatively young field. The seminal article is considered to be "Strategies for Manufacturing", by Frosch and Gallopoulos, which was published in 1989. IE is therefore still grappling with the move from theory to practice (Harper and Graedel, 2004) and much of the literature encompasses discussions on its conceptual basis, from the validity of the ecosystem metaphor (Ehrenfeld, 2004a), to the drawing of boundaries to the field of IE (Lifset, 2005) and whether IE is actually able to be "the science of sustainability" (Ehrenfeld, 2004b, 2007).

The limitations of analysis approaches, as well as the continuing conceptual debate, can also be ascribed to the fact that industrial ecology deals with complex subject matter: Industry is a complex system both in structure and behaviour. The word "ecology" implies that this industrial system has to be considered in terms of the wider social, economic and natural environment it is embedded in, and that the boundaries between the wider environment and the industrial system are fluid. Finally, IE's attempt to drive industry to adopt sustainable development represents a challenge: While there is general consensus that sustainable development is to be pursued, emphasis differs on what is to be sustained, what should be developed, how environment and development should be linked, and over how long a time period sustainable development should be pursued[1] (Boulding, 1991; Parris and Kates, 2003; Welford, 1997). For an analysis that manages to adequately capture these complexities (in as far as the goal of an analysis demands it), understanding of the real world system (the object of analysis) and the problem (the context of analysis) are required. The wealth of information and the lack of in-depth understanding that result from the system and contextual complexity in the case of IE makes the generation of such an analysis approach a challenge.

1.2.1 Limitations of Analysis of Sustainable Development in Industry in IE

The following issues can be identified where scope for improvement exists in analysis in IE:

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[1] On a global level, sustainable development should be a continuous endeavour, but for individual projects specific targets and time limits have to be imposed for practical purposes.

Lack of consideration of system environment and contextual complexity: In the above definition Graedel and Allenby (2003) state that *"the concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them."*. IE prides itself in extending the predominant focus on individual organisations to consider how these are embedded in an environment of other companies through material and energy flows (Korhonen, 2002). However, there is a lack of a structured approach as to how to consider the system's wider natural, economic and socio-political environment. IE, for instance, says nothing about how different values and beliefs of stakeholders should be addressed. A structured approach would, on the one hand, be useful for converting a complex problem, which sustainability issues in industry often create, into a more manageable, clearly defined problem. Furthermore, conditions for every network are unique and solutions may not be one size fits all, therefore the specific context should be considered explicitly. Top-level goals may be universal, e.g. eliminate use of hazardous substances, yet the effectiveness of strategies will depend on the case-specific bottom-level criteria, where it matters what the hazardous substances are, where they originate from, and what options exist to mitigate or avoid these emissions. Decisions concerning sustainable development furthermore always involve multiple stakeholders with different perspectives. It may therefore be that strategies for environmental performance improvement for two similar systems may differ when operating under a different culture, policies, regulatory guidelines, geographical set-up and natural environment. The analysis of industrial systems consequently has to be expanded to include a structured approach that explicitly considers not only the flows of material and energy, but also the context of the technological system. It is also necessary to view any suggested system improvements in the context of the bigger picture (Andrews, 1999), especially if the outcomes are to be used for planning purposes and ultimately for implementation where a bad decision may not be easily reversible. In terms of analysis, structuring has been found to improve modelling and the quality of model outcomes (Leung and Lai, 1997).

Lack of consideration of dynamic nature of the system and its environment: Andersson and Rade (2002), Sagar and Frosch (1997), Oldenburg and Geiser (1997), and Costanza and Ruth (1998) recognized the need to study the dynamics of industrial ecosystems. Bey (2001) pointed out that the analytic frame cannot be merely static, as is the case in most work in the field, but should follow the concepts of development and succession (series of changes over time after a disturbance), thereby maintaining the analogy to natural ecosystems. Industrial systems and their environments are subject to changing conditions, such as changes to technologies, policies and markets. While it may be sufficient to map a status quo in order to gain an understanding of a system, this view may be insufficient if analysis results are to be used for prescriptive purposes, such as strategy design. Limiting the analysis of an industrial system to a status quo may also have the consequence that a strategy that is appropriate now may not be effective for future conditions, for instance if demand for products fluctuates or if new policies are introduced. Dynamic modelling is therefore of particular interest, as it may show trends not obvious when performing static analysis (McLaren et al., 2000).

Lack of consideration of economic and social impacts: *"Factors to be optimized include resources, energy, and capital"* (Graedel and Allenby, 2003). While IE's primary objective is to improve environmental performance, economic and social aspects are also highly relevant considerations for any sustainable development problem. Capital is mentioned in the above definition, yet financial feasibility is not often considered in IE, even though companies and organisation tend to place economic interests first, and costs play a major role in consumer choices and therefore market behaviour. The social benefit or disadvantage gets even less attention even though it represents a sustainability issue according to the EC and WCED (EC, 2001; WCED, 1987). By not considering equity and economics in the focus on system and flows, complexity is lost (Bey, 2001b). Analysis in IE should therefore explicitly consider not only environmental performance, but social and economic performance as well.

Lacking consideration of uncertainty: Knowledge is interpreted information with a strategic value. In order for knowledge to be useful, it has to be based on reliable information. The complexity of industrial systems, i.e. their structure, behaviour and environment may be difficult to grasp. The sustainable development objective adds further complexity by expanding the consideration of the industrial system to include consideration of interconnected social-economic-environmental issues which may be difficult for stakeholders and decision-makers to clearly articulate. As scope and complexity of a problem increases, so does uncertainty. While uncertainty is generally reduced by capturing the real world as closely as possible Zadeh (1973) has pointed out that any attempt to capture the complexity of a system precisely will at some point diminish the ability to make statements of any significance about its behaviour. Simplifications and assumptions are therefore inevitable when trying to describe industrial systems, introducing further uncertainty in the validity of the assumptions.

All these uncertainties can have a significant effect on the reliability of strategies chosen to effect improvement in environmental performance. Yet uncertainty is seldom considered in IE analysis. Only in LCA is uncertainty receiving increased attention (see, for instance, Heijungs (1996), Heijungs and Huijbregts (2004), Maurice et al. (2000), Steen (1997), Basson and Petrie (2007a)). A recent review of uncertainty in LCA emphasises the potential to improve decisions when uncertainty is considered during analysis (Lloyd and Ries, 2007). Decisions based on an analysis where the full effect of uncertainties is known can lead to "better" decisions in that strategies can be designed to hedge against the possible realisations of uncertainty, or the industrial system is equipped with a degree of flexibility allowing it to adapt to changing conditions while maintaining good performance, if this is practicable or possible.

1.2.2 Contribution of Complementary Research Fields

To capture the performance of an industrial system within the context of sustainable development adequately will require more complex models and more sophisticated analysis. Using tools in combination, both analysis and modelling tools, has been recommended to overcome this problem (Robèrt et al., 2002), as well as linking IE to management and policy studies (Korhonen et al., 2004). IE can also benefit from the fact that industrial systems analysis is by no means a new phenomenon. More well established systems research fields can be drawn on to acquire, adapt or generate tools suitable for furthering its research agenda. A number of research fields deal with industrial systems:

- At the regional/global level of the economy and industrial sectors, economics and policy analysis.
- At the inter-firm level of process plants exchanging materials, energy, information and money and providing products to a market, supply chain management (SCM).
- At the intra-firm level of process units exchanging materials and energy, process systems engineering (PSE) is active.

While these fields differ with regards to specific purpose of analysis, in the system scale they address, the spatial and temporal boundaries they draw, these mature areas of industrial systems research use tools that can effectively capture the characteristics and complexities of industrial systems. Some of these tools are common to all three fields, notable examples being problem structuring, simulation and optimisation. The ability of the field of PSE to contribute to the field of IE has been noted by a number of authors (Diwekar and Small, 2002; Diwekar and Small, 1998). However, to date PSE tools have had very limited application in IE (e.g. Casavant and Cote (2004)). Analogies between supply chains and product life-cycles have also highlighted possible links between IE and SCM (Seuring, 2004a). As these fields share the industrial systems view with IE, it stands to reason that the tools these fields have developed can further contribute to advancing analysis in IE.

1.3 THESIS AIM

IE will have to engage with system and contextual complexities to a greater degree if it is to evolve from a conceptual basis to the application of its principles in practice. Authors such as Thomas et al. (2003) have expressed a need for analysis capable of evaluating strategies. **The aim of this thesis is therefore the development of a structured approach to analyse industrial systems for the purpose of identifying strategies to encourage more sustainable development, while accounting for the complexity of the underlying system as well as the sustainable development context.** This approach will combine qualitative analysis and quantitative industrial network models to assess the performance of recommended strategies. This approach will be referred to for the remainder of this thesis as *industrial network analysis*. This analysis is intended to address environmental issues by implementing one or more sustainable development strategies and to allow strategic planning of network structure and development pathway under this strategy. A note on the use of the term “sustainable”: The industrial network analysis proposed in this thesis is driven in the first instance by a desire to improve *environmental* performance. However, while the identification of strategies may have a dominant focus on addressing environmental issues in industry, acceptable, or possibly even attractive, economic and social performance has to be maintained, and hence the strategies are more generally said to foster sustainable development, and not merely environmentally sustainable development.

For this purpose, the industrial network analysis draws on existing tools and frameworks within the field of IE, as well as from systems research disciplines, such as process systems engineering (PSE) and supply chain management (SCM) in the hope of contributing to IE’s potential to quantitatively capture and assess industrial networks, thereby driving the field of IE past its still predominantly conceptual basis towards application (Harper and Graedel, 2004). **The unique contribution of this thesis is therefore the application, synthesis and, if necessary, the adaptation of existing tools to develop an industrial network analysis approach that 1) fulfils the need for an analysis tools in IE that can handle the complexity of the system and system context and 2) addresses the four issues of current IE analysis tools identified in section 1.2.1.**

The most common application of IE is to industrial systems at the inter-firm and regional level. The analysis for this thesis will be aimed at the inter-firm level. At this level it is possible to capture technological detail of industrial behaviour while avoiding excessive simplifications and loss of detail often required to make the system model at the national or global level tractable. The resulting industrial systems are called industrial networks rather than life-cycles or eco-industrial parks as the analysis is not to predefine a specific system structure but should be flexible to fit according to analysis needs and specific situation.

“Industrial networks” in this thesis are defined, in their most general form, as a group of linked, or linkable, units which exercise or contribute to industrial activity through exchange of materials, energy, information and capital. The process components of an industrial network encompass resource extraction, processing and refining, forming and assembly, use, disposal, as well as recycling and reprocessing facilities. These can be existing facilities or facilities proposed as part of an improvement strategy. Industrial networks can be seen as subsystems of the bigger system of national or global industry, and are suitable for exploring sustainable development interventions of a strategic nature.

Throughout this thesis, industrial network refers to a specific configuration of industrial entities outlined above. The concept of industrial networks will be defined further at a later stage in this thesis. By contrast, the term *industrial system* in this thesis is used to refer to any type of industrial cooperation, ranging from integrated unit operations on a process level to interacting sectors on a national economic level. Industrial networks are therefore a type of industrial system.

1.3.1 A Note on the Consideration of Agent Behaviour

Industrial networks are under distributed control, meaning that control of the network rests with many local autonomous agents. "Autonomous" refers to the ability of these agents to intervene meaningfully in the course of events in the system (Giddens, 1984). In the case of industrial networks, these agents encompass government, organizations and institutions active in mining, refining, manufacturing, and product customers, or more generally, the market. Agents manage the part of the industrial network within their sphere of control and interact with other agents based on individual objectives and values. The resulting network development, within the physical constraints of the system, may be completely unrelated to what appears physically and technically viable or even attractive (Axtell et al., 2001). This agent-driven evolution of network behaviour is also referred to as "emergence". In other words, just because it is technically possible and financially lucrative for two agents to enter into a commercial relationship, does not guarantee that they will do so. Agent behaviour thus strongly effects how industrial networks would evolve (Akkermans, 2001; Seuring, 2004b).

Agent behavioural aspects, however, will not be explicitly considered in this thesis. Instead, a **top-down,** or **global perspective** is adopted, where "global" refers to determining preferred sustainable futures for the industrial network as a whole. It can be argued that a top-down approach adopted in this thesis ignores much of the complexity introduced through the behaviour of network agents. This is in fact seen as a weakness of existing analysis of industrial systems by numerous authors (Ehrenfeld, 2007; Nielsen, 2007) especially the lack of attention to consumer behaviour in IE (Bey, 2001; Hertwich, 2005a). Consequently, increasing number of publications explicitly address the influence of agents, their behaviour and how this influences the evolution of industry (Axtell et al., 2001; Kraines and Wallace, 2006). Choi et al. (2001) emphasises that networks should not be left to simply emerge, but some form of overarching control or guidance is necessary to avoid routines, most likely from government or some other regulatory body. Even authors that oppose governmental attempts to control how industry should develop admit that there is a need to provide guidance to government and regulators and to demonstrate to agents the potential of implementing sustainable development strategies and the changes required (Desrochers, 2004; Heeres et al., 2004). Consequently there is use for approaches such as industrial network analysis that indicate what could hypothetically be achieved if cooperation and effective information exchange were possible.

1.4 STRUCTURE OF THESIS

This thesis can be divided into three parts (Figure 1-1): the first, consisting of Chapters 2, 3 and 4, addresses the underlying theoretical concepts underpinning the novel industrial network analysis approach proposed in this thesis. In order to identify sustainable development strategies for industrial networks it is necessary to define the sustainable development issues in industrial networks, identify possible opportunities to address these issues in industrial networks, and to assess the effectiveness of any recommended strategies in a particular industrial network. The industrial network analysis is therefore faced with two challenges: to identify and capture the issues (the purpose of analysis) and to define and capture the system (the object of analysis).

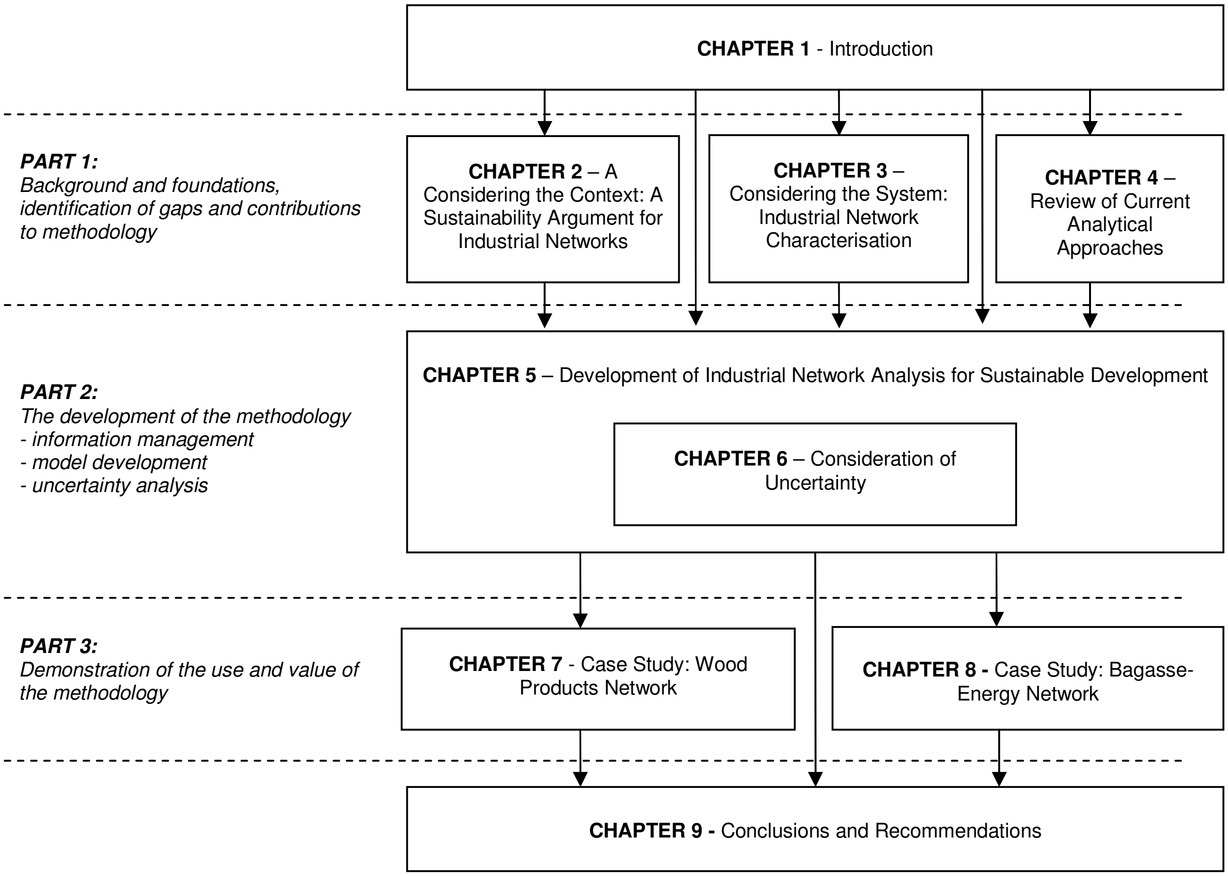

Figure 1-1 Outline of thesis structure and logical connection between chapters.

Chapter 2 engages with the purpose of analysis, and takes up the topic of sustainability in industrial network analysis. It provides a discussion of the environmental issues industry is facing, general approaches recommended to overcome these issues, the barriers to environmentally sustainable development, and possible policy interventions that can make chosen strategies more attractive and thereby may help overcome the these barriers. However, the process of evaluation also requires an understanding of how industry functions. This understanding is necessary to identify the source of issues and what opportunities exist to address these issues. Chapter 3 engages with the object of analysis. In this chapter industrial network characteristics are identified and discussed. This characterisation facilitates network analysis by identifying and articulating the features of complex industrial networks which influence network structure, behaviour and evolution and therefore have to be considered during analysis.

Chapter 4 provides the conceptual basis for this thesis. It reviews and critiques the analysis tools in IE based on the extent to which they capture industrial network characteristics, the sustainable development issues they address and to what extent they address or can overcome the four issues listed in section 1.2.1. Desirable aspects of the reviewed tools used in IE, i.e. aspects that (are able to) address the above issues, will be can then be incorporated into the analysis proposed in this thesis. It will further be discussed how existing mature systems research, such as PSE and SCM tools can be used to overcome the limitations of the existing IE tools.

The second part presents the approach (Chapter 5 and 6). The methodology for analysis of industrial network is discussed in Chapter 5. It constitutes two parts: 1) The problem structuring, which provides a better understanding of the complex problem and thus supports 2) system description (or model generation), where the network is analysed quantitatively. These chapters represent the core contribution of this thesis.

At all stages of the analysis, uncertainty has to be considered. Chapter 6 provides insight to the types and sources of uncertainty, how these can be addressed, and how they affect the chosen outcomes, or in the case of industrial network analysis, the chosen sustainable development strategies.

The third part, consisting of Chapters 7 and 8, demonstrates the application and usefulness of the approach through two case studies. Chapter 7 deals with the concept of resource efficiency in an industrial network created from two distinct wood product supply chains based on pallets and particle boards. The focus on resource efficiency is motivated by the desire to reduce both resource exploitation and waste generation. This case study compares the improvement in network performance possible by assessing resource use on an expanded system-basis rather than on a process or chain level. The robustness of the analysis outcome is assessed through a detailed uncertainty analysis.

Chapter 8 is a more comprehensive case study that uses industrial network analysis to determine optimal allocation of bagasse, a fibrous waste from the sugar industry, for the purpose of renewable energy generation. The use of bagasse for energy generation substitutes fossil fuels, such as coal and oil, and thereby also reduces CO_2 emissions, the major contributor to current global warming crisis. Unlike the previous case study, where network formation was achieved by linking existing facilities, this case study explores the use of industrial network analysis for the purpose of network design, exploring new uses for bagasse. It explores a range of processing options, comprising both existing as well as new technologies and industrial facilities. Furthermore, this case study demonstrates the vital role of the network environment, as the case study is viewed against the background of governmental energy planning targets.

Conclusions and recommendations are summarised in Chapter 9. The chapter includes a discussion of potential future research directions that may spring from this work.

2

CONSIDERING THE CONTEXT: A SUSTAINABILITY ARGUMENT FOR INDUSTRIAL NETWORKS

2.1 INTRODUCTION

In order to identify particular sustainable development strategies for industrial networks it is necessary to first define the general sustainable development issues industry is faced with, and what opportunities exist to address these issues. The insights of this chapter therefore create a "framework" which provides the mental model by which the problem context, and the assumptions and limitations of sustainable development strategies are identified and incorporated into the analysis.

In order to generate and analyse industry's contribution to sustainable development strategies, one first needs to develop an understanding of the particular issues that make current industrial activity environmentally unsustainable, as well as the means available to tackle these problems. For this purpose the following aspects will be discussed in this chapter:

1. The generic sustainable development issues associated with industrial development (Section 2.2)
2. Possible means to overcome these sustainable development issues (Section 2.3)

3. Any potential barriers that exist to the implementation of the proposed improvement strategies (section 2.4)
4. How these barriers may be overcome through the use of policy interventions (section 2.5).

These aspects are well documented and discussed in literature and hence will not be discussed in great detail here. Reasons for discussing the issues, strategies, barriers and policies are twofold: 1) The listed issues and strategies form the basis the environmental analysis and management tools that IE currently draws on. 2) This chapter serves to illustrate the generic strategies recommended for environmental performance improvement in IE literature that can be evaluated in the industrial network analysis. In addition it explores what barriers to sustainable development exist and which of these barriers can be addressed by the analysis and how far policy interventions can be interrogated.

2.2 SUSTAINABLE DEVELOPMENT ISSUES IN INDUSTRY

Environmental sustainability issues arise in industrial networks from the following sources (Ayres and Ayres, 1996):

- Use of non-renewable resources
- Use of hazardous materials
- Low efficiency
- Waste creation and disposal
- Rising consumption

The overexploitation of renewable resources is added to this list. These issues span all of industrial activity, form harvesting or mining of required resources, to the emissions and waste disposal to the environment, encompassing the processing of these resources and the use of the resulting products. In industrial networks these issues may occur individually, or one issue may dominate, but it is more likely that several issues may be identified in light of the fact that several facilities are involved.

2.2.1 Use of Non-Renewable Resources

Any consumption of non-renewables equates to quasi-permanent[2] depletion of the natural resources stock and is therefore inherently unsustainable (Huesemann, 2004). These resources have no intrinsic value in

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[2] The resources may in fact be renewed, but over geological time-frames.

the form they are found in nature, as minerals, oil or coal lying latent in the earth's crust. Only when extracted and processed into such products as copper, gasoline and electricity do these resources provide some service to society and thereby obtain value. However, the extraction, processing and use of non-renewables resources have significant environmental impacts. Metals are dilute in the earth's crust. The delivery of one tonne refined metal involves the removal and processing of anything between four tonnes of ore (in the case of aluminium) and several thousand tonnes in the case of uranium, platinum group metals and gold. Minerals are also thermodynamically stable and extracting the metals is extremely energy intensive (eg. thermally via smelting or chemically via acid leaching). Coal and oil are the major global sources of energy. With these resources, it is primarily the combustion products containing CO_2, SO_2 and NO_x that cause problems, contributing to climate change and acidification impacts. The benefit of using the resource therefore has to be weighed against its environmental impact and ultimate social and economic costs. Ceasing to use these resources would mean that current and future generations do not have access to the associated benefits. A more appropriate approach to using these resources may therefore be to increase the functionality obtained from each unit. This process of dematerialisation can, however, only be pushed so far. Ultimately the resource will be exhausted, unless substitutes for the resource can be identified.

2.2.2 Use of Hazardous Materials

Industrial networks also create and utilise hazardous materials, which are used due to other attractive properties they possess. Examples of such substances include toxic heavy metals used to preserve timber (e.g. chromium, arsenic), radioactive uranium for power, or carcinogenic substances such as some brominated flame-retardants. In light of the damage these substances may inflict it has to be questioned whether these materials should be used in the first place, and whether they could be replaced by other materials that have similar desirable properties, but are less harmful to the environment. If no viable substitute for the hazardous material is available and the purpose to which it is used is perceived to be impossible to do without, then careful management and recycling is required to avoid the hazardous substances dissipating and accumulating in the environment. However, it is not always possible to tell in advance if a material will be hazardous and there will inevitably be surprises (Ayres and Ayres, 1996).

2.2.3 Overexploitation of Renewable Resources

Renewable resources, such as sunlight, wind or agricultural products are deemed preferable over non-renewables resources. This is because these resources are seen as "natural": i.e. because these resources originate form the natural environment and are more easily replaced, it is assumed that they are delivered at less cost to the environment than non-renewable resources which are not readily regenerated or assimilated by nature. However, their growth and/or harvesting, processing and use can still have significant adverse environmental impacts. Growing of crops and livestock, for instance, often requires significant input of water, fertilizers, energy and land. For example, soybean production and cattle ranching in South America drives deforestation of the Amazon, leaving native animals with smaller and smaller refuge areas which simultaneously become more accessible to poachers. This ultimately leads to a loss in biodiversity which can have detrimental consequences on eco-system health. Intensive agriculture also contributes to the loss of topsoil and erosion and the soil subsequently becomes drained of nutrients without input of large amounts of fertilisers. The excessive use of these in turn can create problems with eutrophication in nearby water bodies (see e.g. Gelbrecht et al. (1996), Daniel et al. (1998), Bowen and Valiela (2004)). Overfishing on the other hand is threatening to wipe out entire fish species thereby preventing future generations from enjoying and benefiting from these valuable sources of food (see e.g. Allsopp et al. (2007), Myers and Worm (2005), Sala and Knowlton (2006)).

2.2.4 Waste Creation

Wastes are generated and released to air, water and land all along a product life-cycle, from resource extraction, processing to use and disposal. Wastes are undesired materials, energy, by-products or end-of-life products generated during material harvesting, processing and use. The extent of environmental impact of a waste release depends on nature’s ability to absorb it. This assimilative capacity of nature is not only governed by overall quantity that is to be assimilated, but it is also affected by the rate of discharge, the possible mobilisation of waste in nature and the reaction and interaction of this waste with its environment.

Since the industrial revolution the prevalent environmental management attitude to waste release has been of the “foul-and-flee” variety (Jackson, 1996). When land was abundantly available, human settlement small, and the material basis of society simple, it was possible to move away from adverse environmental effects. As this became less and less acceptable, attitudes moved progressively from “dilute and disperse” to “concentrate and contain”. These forms of environmental management attempt to either capture emissions at point sources to prevent them entering the environment, or to dilute emissions to the extent that they are no longer a threat. These approaches leave the underlying processes and products largely unchanged. However, while it is theoretically possible to contain materials over geological time frames, in many cases it has proven difficult to contain toxic or hazardous substances for even a couple of decades. Dispersion is also not always an adequate solution, as natural processes rely on transport and accumulation. While nature has the ability assimilate many substances, many synthetic chemicals take much longer than “natural” materials to break down. If emissions continue to be generated in large quantities over the long term, and nature is slow to assimilate these wastes, then the concentration in the environment will soon rise back to harmful levels.

A more sophisticated approach, which is still prevalent, is to deal with the waste in the form of end-of-pipe treatment and remediation (Ayres and Ayres, 1996). End-of-pipe treatment captures wastes from point sources and often only serves to capture waste and making it somehow less harmful, or stable. Sewage treatment breaks down waste, filters redirect emissions to air into solid waste to be disposed to landfill, catalytic converters turn poisonous CO into less harmful CO_2. Where contamination of the surrounding biosphere has already occurred, such as during leaching of hazardous materials from a toxic waste dump, or accidental chemical spills, remediation of the area may become necessary to erase or mitigate the damage. This is an extremely costly approach with limited effectiveness and in the worst cases damage can persist for generations. Attempts to remediate the site in many cases have limited effectiveness and complete clean up would require an excessive input of effort and funds. As an example, poisonous sludges from former East German smelters are continuing to pollute the Elbe, despite attempts to remediate the contaminated sites.

2.2.5 Low Efficiency

Waste generation is in many cases also related to the efficiency with which a resource is converted into a product. This applies to an individual process or plant (technological efficiency), as well as the overall supply chain or network (resource efficiency). Mass balance closure dictates that every unit of waste is a fraction of resources not ending up as valuable product. It would therefore be a win-win situation for companies if they would either reduce the waste they release through internal recycling, more efficient technology, or through selling it to some other process as a raw material. However, efficiency cannot be improved *ad infinitum*. In many mature industrial processes efficiency has been pushed as far as the physical limitations allow. Modern petroleum plants, for instance, produce relatively little waste. All components of the crude oil are used to their maximum extent, or converted into useful products[3].

The disposal of wastes and especially post-use products means that the materials and any embodied energy of the materials is lost for further use, unless the waste dumb will be mined at some stage in the future. This, in turn, requires new virgin resources to fill the demand, further driving renewable and non-renewable resource use.

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[3] However, while all material is converted into potentially useful products as far as possible this is not a guarantee that they will find suitable markets. For instance, significant amounts of natural gas are may be flared and sulphur stockpiled if it is uneconomical to sell these products.

2.2.6 Rising Consumption

The consumer market is arguably the most powerful influencing factor on industrial operation, as its demand for products and the revenue this provides are the reasons for an industrial network's existence. While industrial practices are often criticised for their role in environmental degradation, little has been done to address the (lack of) sustainability of current consumption practices (Hertwich, 2005a). The resource use of the global consumer class is already too much for the planet to bear. The problem is caused by the push for companies to grow through expanding markets and consumers" willingness to acquire material wealth for reasons such as personal happiness and showing of status. This is compounded by the fact that "*if developing countries are to reach the level of per capita income now enjoyed by Western countries, there needs to be a 46-fold improvement in technological efficiency just to hold resource consumption and environmental emissions at current levels*" (Goodland and Daly, 1993). From a purely social perspective, it should be supported that citizens in developing countries be able to share the high standard of living enjoyed by residents of first world countries. China's and India's rapid economic development, for example, is allowing its citizens access to better education, health care and general quality of life. However, much of this is achieved at the expense of the environment as resource demand has risen sharply and production practices are not always clean. Technological progress alone is therefore unlikely to be able to bridge the gap (Keyfitz, 1998).

In a first world consumer society, most consumers are seldom directly confronted with the consequences of the excessive consumption. The product appears in a shop and disappears in the garbage bin, without the consumer ever having to ponder the environmental cost of his choice, at least not directly. There is also a lack of awareness of the physical limitations of anthropogenic processes. Many consumers believe that political intervention and technological developments will be able to compensate for the increased demand and that environmental impact will therefore be avoidable or rectifiable. However, the attitude is changing as consumers are becoming more aware and more interested in the "*world that lies behind the product they buy*" (Robins and de Leeuw, 2001).

While choosing more environmentally friendly products is a step in the right direction, many impacts could be avoided or reduced if fewer products were consumed. In fact, many economists are promoting the idea that continued economic growth is at odds with the physical limitation of this planet (Ayres, 1995, 1996; Daly, 1992; Daly, 1993; Victor and Rosenbluth, 2007). But how is sustainable consumption to be encouraged? The literature on the subject can be divided into two categories (Zukin and Maguire, 2004): The one category focuses on the ills of over-consumption, the other on analysing the behaviour and social-institutional settings shaping consumption. However, the literature in the latter category is criticised for not asking sharp questions, instead rather focusing on empirical observations. Ethically based literature asks questions about the wisdom of ever increasing consumption, and investigates what drives people to excessive consumption.

Despite the research interest and starting debate, no ready means of changing this behaviour have been identified. This is not surprising in light of the fact that consumer behaviour is a complex social and psychological issue. A move to a culture of reduced consumption would require a fundamental shift in the mind set of consumers, and it would mean a fundamental change for an industrial network driven by the principles of economic growth. Until the time that this shift occurs, industrial network will have to maximise the benefit and minimise the impacts from the use of its available resources.

2.3 STRATEGIES FOR SUSTAINABLE DEVELOPMENT IN INDUSTRY

As waste releases became less and less acceptable, with tightening emission limits, stricter environmental standards and increasing disposal costs, industry is increasingly looking into minimising wastes, while simultaneously improving the environmental performance around the mining, harvesting and use of resources. This trend to avoid the problem, rather than treating the symptoms has been described as upstream thinking (Robert, 2000; Robert et al., 2002). In other words, focus is shifting to maximising resource productivity, thereby reducing environmental impact. Ayres (1996) suggested the following strategies that attempt to improve industrial performance by taking a more holistic approach to managing resources and materials.

1. Substitution of scarce or hazardous materials
2. Dematerialisation
3. Reintegration
4. Waste mining

However, it may in many cases not be possible to completely eliminate waste or find further use for it. In these cases waste management is the only alternative.

This list of strategies is similar to sustainable industrial management strategies proposed by Kandelaars (1999), Erkman and Ramaswamy (2001) and Thomas et al. (2003). Kandelaars and Thomas explicitly add technological innovation, which is the successful exploitation of new ideas, to the list, however, this can be seen as a means to achieving one or more of the four above listed strategies.

Based on the issues existing within a particular industrial network, these strategies may be deployed individually or in combination. These strategies are discussed in more detail in the following sections.

2.3.1 Substitution

Substitution attempts to avoid and reduce use of scarce or hazardous substances by replacing them with more abundant, less harmful ones, or alternatively with services (Thomas et al., 2003). It addresses the issues of resource exploitation and the generation of harmful wastes. For instance, brominated flame retardants have been identified as hazardous due to their environmental persistence, ability (in many cases) to accumulate through food chains and chronic toxicity (Alaee and Wenning, 2002; de Wit, 2002). Santillo and Johnston (Santillo and Johnston, 2003) therefore recommend to look beyond options for simple chemical-for-chemical substitution to alternative materials and designs. The alternatives include non-brominated chemical additive, material substitution or changes in design and construction to render products inherently less flammable. Construction of television sets with greater spacing or metallic barriers between components, or which use lower voltage components, are examples of the latter (Lassen et al., 1999). In most cases, however, substitution has been driven by cost considerations and identification of substances with superior performance. For instance, weight has a significant affect on transport impacts, which include costs as well as emissions. As a result, aluminium and light weight plastic packaging is becoming more common, whereas the comparatively heavy glass is used less and less.

However, there are limits to substitution. While substituting substances and technologies has been successful in many cases, and while there is still scope for optimising many technical problems, this does not ensure that this is (perpetually) possible for all goods and services. Some substances have properties that make them unique and not easily replicable by other substances. Copper, for example, has properties which make it an ideal electricity conductor. While both silver and aluminium could function as substitutes, the former is too rare and expensive, the latter not as conductive, resulting in greater losses (Ayres, 2007). In many cases cost considerations have driven substitutions.

The implementation of substitution can be driven either through product and process redesign, technological innovation or through policy. Substitution of one material for another may affect product design. It will therefore not only have an effect on individual facilities, but on the entire network structure. Substituting one raw material or product for another will require a switch to, or possibly even establishment of, a different supply chain. In response to the new input, new technologies may have to be incorporated or entire new processes designed. If the substitution of materials leads to changed properties in the product, the customers or further processors in the network may also be required to adapt. An additional consideration is that the redesign or substitution of products may also affect the degree to which a product or material may be reintegrated. If hazardous substances are removed, or a product designed for easy disassembly, reintegration will become easier, and again the facilities and processes required will be affected.

2.3.2 Dematerialisation

Dematerialisation involves redesigning products to deliver the same function with less material input. A classical example is the electronics industry, where the functionality of home entertainment systems, computers and cell phones has expanded in leaps and bounds, while the devices themselves continue to get smaller and lighter. Alternatively products can be substituted by services, for instance cars through public transport[4].

The effect of dematerialisation on industrial network structure and management is similar to substitution, as dematerialisation also requires changes to the product design and potentially the materials required. The implementation of dematerialisation will therefore affect the entire network structure through a ripple effect. However, the effect may be less severe than for substitution in those cases where no shift from one material to another takes place, but where dematerialisation in a product simply involves a reduced demand for raw material. Dematerialisation can also be driven either through product and process redesign, technological innovation or policy.

2.3.3 Reintegration

Reintegration is more commonly referred to as recycling; however, in this thesis recycling is specifically used to describe a specific type of reintegration. The term reintegration is therefore used as the collective term to avoid confusion. Reintegration involves the practice of prolonging a discarded product's, product part's or other waste material's lifespan by integrating it back into the supply chain it originated from (also called closed loop recycling), or into another supply chain or network (open loop recycling). Through the use of old available materials and products, materials are diverted from disposal, and at the same time the amount of required virgin resources is reduced. Reintegration of materials has many practical challenges, as waste streams vary immensely in their characteristics: They can be homogeneous, such as a spent solvent stream, or heterogeneous, comprising a variety of constituents, as is the case with, for instance, municipal waste. Waste can be of high quality, meaning that it can be used again either directly, or with little additional processing. Or it can be of low quality, implying that it needs extensive processing to make it suitable. In response to this there are different levels of recycling (Figure 2-1). These levels of recycling include, in order of preference:

- Reuse and repair
- Remanufacturing
- Recycling

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[4] For such a strategy to work consumer attitude would have to change. Many people are unwilling to sacrifice the convenience and flexibility an own car affords them, especially if public transport is limited, unreliable or expensive.

If the waste is of sufficient quality, i.e. retaining its functionality, then *reuse or repair* may extend the material's life, thereby avoiding the impacts associated with the delivery of a virgin material and products. Reuse is the next best option should avoidance or reduction be infeasible. This is only possible in those cases where the waste is still able to fulfil some useful function without requiring any intermediate processing. The waste can then be reused either onsite or somewhere else in the industrial network.

If the product is discarded with no interest or opportunity for repair and reuse, it can be collected and some *remanufacturing* can restore its functionality or make it suitable for another application. More highly degraded products may have to be disassembled and/or broken down in order to at least allow the recycling of some or all of the constituent materials. These activities are not mutually exclusive. In a population of released products, some may be landfilled, while another fraction may be suitable for remanufacture and another too degraded and thus only suitable for recycling.

In the case that the waste has no further use, or where it is not cost effective to exploit the waste for this use, the components or constituent materials can still be recovered. *Recycling* requires a degree of processing to recover the components and materials that still have some use or value. The energy intensity of this processing is primarily dependent on the complexity of the waste.

While reintegration of wastes decreases the demand for virgin raw materials and the amount of waste disposed to the environment, it is important to consider that processes necessary to enable reintegration has impacts associated with it, such as emissions, water and energy consumption. The less processing is required to reintegrate materials, the less environmental impact the reintegration in turn is likely to have. The environmental benefit therefore decreases from reuse to recycling.

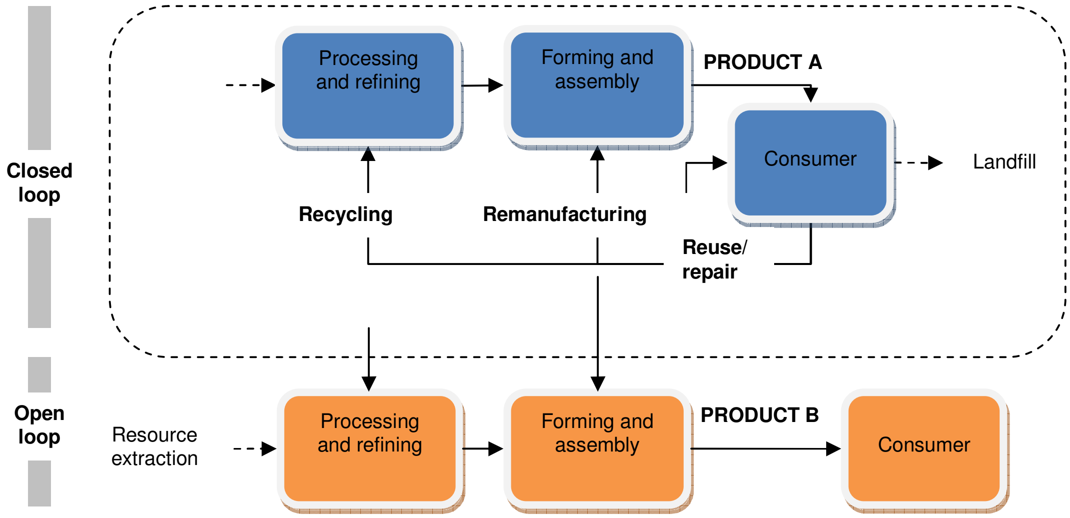

Figure 2-1 Possible reintegration options. The reintegration option chosen depends on the quality of the waste and the waste stream. While the waste stream originates from the "customer" in this case, the waste can originate from any industrial network unit.

Treatment and disposal processes are managed internally by the individual industrial facilities. Reintegration on the other hand requires cooperation with other industrial facilities in the network if the waste is not reintegrated onsite. These strategies therefore influence the wider industrial network, requiring cooperation amongst industrial network members to succeed.

As already indicated, product or waste complexity plays an important role in that increasing complexity, i.e. degradation and heterogeneity of materials, makes the reintegration structure in turn more complex and hence more costly and energy intensive to operate. The more complex products require more complex reprocessing which is in turn is more costly and energy intensive. Recycling structurally simple, single constituent items like plastic bottles is easier than, for instance, repairing radios, which requires the identification of the make and model, identification of the damage, procuring specific spare parts, repairing, and tracing of each unit so it can be returned to the original owner. Unless the product, or its constituents, is valuable enough to justify the associated costs and effort, complex products may be less amenable for reprocessing.

While waste is generated at every stage along a product life-cycle, processing facilities are generally intent on maximising efficiency and minimising waste. Arguably the most significant source of waste is therefore the disposal of the old products. Industrial networks can comprise facilities or supply chains generating a range of products and subsequently several markets exist which will ultimately release these materials. Different products tend to have different demand rates, different use durations and different requirements for reintegration due to different product properties. This introduces significant uncertainty in predicting the quantity, quality and timing of materials as they become available and matching these with demand (Guide Jr. et al., 1999; Guide et al., 2000). This is in contrast to product manufacturing stages, where supply, demand and material and product specifications are rigidly controlled. The practice of reintegration introduces complexity into both the supply and demand-side management that are not present in classical linear supply chains utilising only virgin raw material (Fleischmann et al., 2000). Product take-back has been shown to be advantageous in terms of both sales and profit margins for individual companies engaged in it (Heese et al., In Press), however, the reintegration system has to be well designed (Realff et al., 2000b).

However, reintegrating material may not only bring environmental benefits. The first problem is that material flows in industry tend to be diverging overall: For instance, iron may end up in construction material, transport equipment or in industrial machinery (Wang et al., 2007). An increasing input of energy would therefore be necessary to gather the material and reintegrate it and restore it to a useful state. Secondly, material and products tend to degrade with continued use. Thirdly, unless waste products are very cleanly separated before disposal, for instance through separation of glass, aluminium or paper, waste may only be available in a heterogeneous waste stream or stock. This represents an increase in entropy which requires energy input to overcome if materials are to be collected, separated and reprocessed to their original state.

Reintegration in industrial networks may serve to substitute the use of non-renewable or overexploited renewable resources while simultaneously reducing the amount of waste disposed. This strategy will affect the entire industrial network. Reintegration will affect the virgin resource supplier by taking over (part of) its market, but potentially also the supply chain in which it is integrated if the material quality differs from that of the virgin material and the facilities using the alternative material have to adapt their processes, or if the quality of the product is affected and hence the customer satisfaction or pricing of the product.

2.3.4 Waste Mining

Waste mining refers to the reclamation of useful substances from waste streams. Ayres (1996) uses the separation of sulphur from flue gas and the extraction of precious metals such as gallium, cobalt, silver and gold from slags or gangue generated during copper, lead or zinc mining as examples. Where reintegration refers to the reclamation and reuse of previously valuable substances which have lost value and/or functionality through use, waste mining refers to extracting material of value from a waste stream that was created during the production of potentially unrelated materials and products.

Extracting the useful substances from the waste may in some cases be more difficult than extracting it from natural resources. However, as the waste stream may incur a disposal cost, it may be worthwhile to offer subsidies to encourage waste mining. Economies of scale are therefore also critical in this case. Similar to reintegration, waste mining in industrial network may also serve to substitute virgin resources, if waste mining is not the dominant source of the materials in the first case, while also reducing the quantity of waste. Once the necessary technology for waste mining would be added to the network, the strategy of waste mining would in the first instance provide competition to other suppliers of the material, but it is not expected to have a great impact on any down stream processes using the material.

2.3.5 Waste Management

In those cases where waste cannot be avoided the waste will have to be managed. A well known example of environmental impact mitigation is the waste management hierarchy. This framework recommends four general strategies on how to manage waste. (Different permutations of this have been developed for specific cases. See, for instance Al-Ansary and El-Haggar (2005) who include regulation, rethinking and renovation to a waste management hierarchy for construction waste). It is often applied at particular facilities, but the approach is extendible to manage waste from multiple facilities in an industrial network. The waste management hierarchy puts waste management methods in the following order of preference:

1. Avoid or reduce
2. Reintegration
3. Treat
4. Dispose

The waste management hierarchy overlaps with Ayres's classification in that it, for waste specifically, advocates substitution and dematerialisation (avoidance and reduction) as well as reintegration.

End-of-pipe treatment and disposal of waste were already listed in section 2.2 as being potential challenges to sustainable development in industrial networks. However, end-of pipe treatment is acceptable if it turns a waste into either an inert and environmentally harmless substance, even if disposed in high quantities, or into another potential resource. Other means of waste treatment include incineration and composting. However, as both these processes convert waste to a useful form, namely heat and fertiliser, these waste management options can also be seen as a type of material reintegration.

Disposal should be acceptable only in as far as the waste can be assimilated and processed within nature capacity to do so. In general, however, disposal should be avoided for two reasons: Firstly, it implies dissipative use of resources and thereby a loss of their functionality to society. In this instance the resources should be recovered and cycled within industrial network as far as possible to maximise the use before drawing on virgin resources. Secondly, the disposed material may be hazardous either due to its quality or the quantity of its release. However, if the waste is hazardous any release to the environment should be avoided. Either this waste has to be somehow recycled or, failing that, the waste has to be avoided as far as possible.

2.3.6 Level of Improvement

The level of ambition and the scope, or the "levels of improvement", of the proposed strategy can range from small scale incremental changes, to fundamental system shifts (See Figure 2-2). Reintegration of waste material or by-products, for instance, can be instituted at an individual facility. Alternatively, and more attractively, reintegration of material can be implemented, if possible, on an entire network level, in which case more facilities, more material, more time and effort are involved.

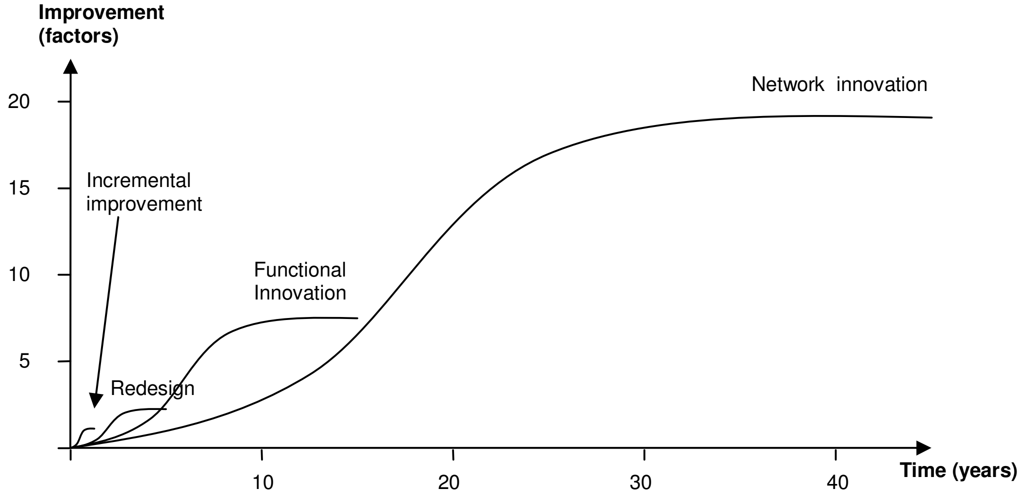

Figure 2-2 Level of improvement (adapted from Brezet (1997)).

Most of the environmental improvement effort involves incremental improvement, addressing the performance of existing products, technology and management methods (Wrisberg and Udo de Haes, 2002). Incremental improvement is comparatively easy to implement and hence also the most widely practised: It involves only a small number of products and processes and can therefore be done within a company or facility. The benefit to incremental improvement is that the comparatively small changes deployed by smaller network entities, i.e. companies or facilities, can be adopted and tested quicker than more ambitious strategies aimed at larger systems, such as industrial networks (Holling, 2001). It is relatively short-term and less resource intensive with regards to people, time, money and information than more ambitious strategies. Incremental improvement involves, for instance, the addition of end-of-pipe technology, a change to process operation, or use of slightly better product. Incremental improvement can, however, be part of a more ambitious strategic development if a number of small steps contribute to overall improvement in network performance.

Promoting functional and network innovation on the other hand promises greater improvement than a single incremental improvement, however, it is more difficult to implement the changes as the scope of the intervention increases. Functional innovation involves, for instance, developing a different way to deliver the same service. An example of functional innovation is the development of energy saving light bulbs to replace conventional incandescent ones which convert most of the energy to useless heat. Network innovation involves a fundamental change in how an industrial network delivers products or the even the type of products or services it delivers to fulfil a certain need. An example of network innovation would be a departure from a fossil fuel based energy economy, to a renewable energy economy. This will involve a complete change in how electricity is generated (many distributed generators using a range of energy sources rather than a few large generators based on a single resource), transmitted (smaller grids) and used. Clearly, the higher the level of improvement required, the more extensively the industrial network is affected, and the greater the time and effort necessary to implement the envisaged strategy.

The proposed industrial network analysis of this thesis has the benefit that, by taking the systems view as well as time-dependent change into account, it will be able to assess strategies ranging from incremental improvement to network innovation. However, network innovation strategies are difficult to examine for two reasons: 1) These types of strategies are not always readily apparent and 2) there is likely to be less reliable information available than when analysing the effect of incremental changes. Should entirely new technologies be deployed, there would be a lack of information regarding its performance. In addition, the acceptance amongst business and society of radically new means of delivering products and services may be uncertain. This again highlights the importance of considering the effect of uncertainty on the reliability of results.

When considering these strategies, it has to be kept in mind that there may be practical barriers to the degree to which they can and will be implemented, such as physical and economic feasibility, institutional barriers, lack of knowledge about damaging consequences of certain actions or a simple lack of time to act before more damage is done. These are discussed in the next section.

2.4 BARRIERS TO SUSTAINABLE DEVELOPMENT IN INDUSTRY

2.4.1 Physical Barriers

The strategies discussed above are only practicable as long as they are physically feasible. In some instances, there may be no known substitute for rare or toxic materials, or it may not be possible to substitute a raw material for another without significant deterioration in product performance. Technological efficiency gains may be close to or already have reached physical limits. Products design may have been optimised, leaving little room for further improvement. Dissipative use, as well as the complexity and associated energy-intensity of reintegration the majority of materials pose the biggest challenges in implementing increased reintegration of materials (Malcolm and Clift, 2002).

Another physical consideration is the need for energy to drive any and all industrial processes. The larger the industrial activity, the higher the required energy input to maintain the network. The energy requirement also ties in with entropy. In thermodynamic terms, most natural resources have a high degree of “disorder” or entropy. Metals are contained in low concentration in ore. Gasoline is but one fraction of all the hydrocarbons that make up crude oil. To increase order, i.e. to concentrate and extract the desired components form the resource requires significant amounts of energy to be put in. Entropy increases again in those cases where the now pure, low entropy materials are mixed or assembled with other materials to form a final product. This entropy increases even further once the heterogeneous products are mixed with other wastes. This is where reuse or recycling can become challenging. To separate and extract certain desired materials, components or products from a stream of numerous diverse components again requires significant energy input. This energy requirement may in some cases exceed what is economically of even physically feasible.

2.4.2 Economic Barriers

There are also economic considerations. Opportunities to close material cycles, to adequately treat hazardous waste, or to substitute non-renewable, overexploited or hazardous resources may exist, but these may not be cost effective, at least not on the small scale. Research has however shown that in the case of eco-industrial parks, the cooperation resulted more from financial gain then environmental benefit (Tudor et al., 2007). The most often heard complaint is the high cost of upgrading and maintaining a cleaner process. Cost will be even more extreme if fundamental restructuring is required as it is currently being called for in the energy sector to mitigate carbon emissions. Even in cases where a return on the investment can be theoretically demonstrated, network agents[5] tend to resist a change to unknown, or less known, technologies and practices. This is due to the perceived risk of such a change, as well as the associated transaction and switching costs. Conversely, resources may not be adequately valued, or in other words costly enough. Low value (waste) materials may not be cost effective to transport over long distances and will therefore have to be used onsite or exported to another facility nearby. Also, the price of environmental damage may not be adequately reflected in the cost of a product, otherwise environmentally beneficial practices would become more cost effective. Pressure on many resources can also be exacerbated by the fact that they are free to use or very cheap, which encourages greater use than would otherwise be the case (Moxnes, 1998).

2.4.3 Other Barriers

The physical and economic barriers can be explicitly included in the industrial network analysis as constraints that may or may potentially be overcome by means of technological advancement or policy instruments. However, there are several other barriers which cannot be explicitly captured (adequately) in the quantitative network analysis. This is primarily because the mechanisms underlying these barriers are

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[5] An agent is defined as a person, company, business, organisation, institution, consumer or other stakeholder that exerts some form of significant influence on the performance of the network and is in turn affected by the network.

too complex to allow adequate representation of how they come into effect when certain strategies are implemented in a network. These include technology lock-in, institutional barriers, ignorance and slow recovery of the natural environment even if the issue has been adequately addressed. While it may be of interest to show the network performance achievable if these barriers did not exist, these barriers could also be considered *qualitatively*. Assumption about the viability of strategies can be influenced by the consideration of these barriers and analysis outcomes interpreted with these barriers in mind.

2.4.3.1 Technology lock-in

Technological development exhibits path dependence (David, 1985), which means that how a technology or even an entire network will develop in future is to a large extent dependent on its historical development. Arthur (Arthur, 1989, 1994) argued that the increasing returns to adoption (including economies of scale, learning effects, adaptive expectations and co-ordination effects) could result in technological lock-in, where incumbent technologies are effectively locked in and the take-up of new, more environmentally sustainable options is prevented. Many current techno-institutional systems are both unsustainable and locked-in, for example, the so-called carbon lock-in of current fossil fuelled energy systems (Foxon, 2007; Unruh, 2000).

The adoption of new technologies may form part of any of the sustainable development strategies listed in 2.3. Reintegration may require new technology capable to upgrading the secondary material or extracting the valuable material from a heterogeneous waste stream, substitution technology capable of achieving similar functionality in a product while dealing with a different raw material, and dematerialisation may necessitate new methods of production. Industrial network analysis can serve to highlight the potential improvement in environmental performance that the new technology brings to an industrial network, and analysis results could be used as a basis of discussion, or further analysis, to determine how the drawbacks (e.g. high costs) could be addressed, or what incentives would make adoption more attractive.

2.4.3.2 Institutional barriers

Decisions in regards to environmental management are taken at a company level, yet in order to promote sustainable development on an industrial network level government in many cases wishes to exert a degree of control. This control comes in the form of policy and regulatory frameworks and these play a vital role in fostering, for instance, innovation (Hodgson, 1988; North, 1990). While policy instruments are designed to overcome barriers to sustainable development, which is how they presented in the following section, a lack of or badly executed policy may become a barrier instead. The UK, for instance, has a long-term policy goal of reducing CO_2 emissions by 60% by 2050 (DTI, 2003). Achieving this target will require radical, systemic changes to UK energy systems, including the development of technologies that are currently uneconomic in mainstream markets. On the other hand, the design of policy instruments, such as the Renewables Obligation[6], runs the risk of only supporting the available commercial renewables and so enshrining what is currently economic (Foxon and Pearson, 2008). Another problem with creating effective policy to foster sustainable development is that long-term environmental problems tend to receive relatively low priority in the face of more immediate policy pressures. Furthermore, the complexity of the sustainability issues and the consequent uncertainties in future costs and benefits are not easy to address within current processes.

Furthermore, there are indications that too much governmental involvement in general may be counter-productive (Desrochers, 2004). In empirical studies of eco-industrial park developments in the US, it has been observed that heavy government involvement has resulted in US companies in general not being interested in such projects. In the Netherlands, on the other hand, projects fostering eco-industrial park developments proved more successful. In this case the projects are mostly initiated by the companies themselves with financial and advisory support from the local and regional government (Heeres et al., 2004). There is no definitive answer to how best to manage sustainable development in industrial networks, however, industrial network analysis could be used to demonstrate to agents the potential benefits of different strategies, and what actions would be required to achieve this. In such a case, industrial network analysis could be used as an iterative tool, were the strategies could be adapted based on agent feedback to assess a variety of possible network development pathways.

2.4.3.3 Lack of knowledge

Another barrier to sustainable development is lack of knowledge. This can be ignorance about the issues, lack of knowledge about the system, or lack of knowledge about potential solutions. A lack of understanding underlying ecosystem complexity has resulted in environmentally damaging activities being engaged in, and continuing, even after damage has already occurred, because the effect was not immediately connected to the appropriate industrial practice that caused it. The precautionary principle is an attempt to avoid such situations by assuming a suspected industrial activity of being “guilty until proven innocent”. However, to continue the analogy, some time may pass before a suspect is identified, or suspicion has reached a level deemed sufficient to act on. If part or the entire industrial network is suspected of contributing to environmental harm, then the suspected issue could be addressed with the strategies discussed in 2.3. If, however, an issue is not yet observed, or no source suspected, then it is impossible to address.

Ignorance also extends to a lack of understanding of the network. Eyre (1997) mentions the complexity of the energy system as a barrier to the adoption of energy efficiency measures in the energy sector. It is

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[6] http://www.dti.gov.uk/energy/renewables/policy/renewables_obligation.shtml

unclear, for instance, how liberalisation of energy markets will affect prospects for energy efficiency. However, it is not only network complexity that affects the understanding of how effective a strategy will be. As was discussed in the introductory chapter of this thesis, the complexity of the sustainability context and the complex interaction of the network with its environment should not be underestimated. The former makes it difficult to define what exact issues are to be addressed, the latter makes decisions more difficult with regards to how issues are to be addressed. Industrial network analysis therefore expressly attempts to engage with the complexity of industrial networks. While there are limitations to the extent to which complexity can be captured, for the reason that some degree of simplification will be necessary to make the problem (mentally) tractable, the active engagement with complexity is expected to allow better informed decision to be made with regards to strategy development.

Finally, the reason that sustainable development strategies are not adopted may be attributed to a lack of knowledge about what possible strategies exist. This barrier could be overcome by education, for instance by presenting the success of certain strategies in other networks, or through marketing of new technologies to raise awareness. Industrial network analysis results could also be used, illustrating the possible performance improvement resulting from the use of a strategy based on new technologies or approaches to operation. However, lack of knowledge about how the strategies should be applied and how they will affect facility or network structure and operation is expected to be the more common barrier. (The latter ties in with the network complexity argument in the preceding paragraph.) For instance, a study of eco-industrial parks (EIP) in Asia,, by Chiu and Yong (2004), revealed that a lack of a clear understanding of what constituted an eco-industrial development and a failure to understand the specific potential of industrial ecology kept agents from entering cooperation. Similarly, the uptake of new, more efficient and cleaner technologies is attributed to lacking knowledge transfer and skills development (Foxon and Pearson, 2008). For industry in general, it is therefore important that knowledge transfer is encouraged and assisted, for instance through appropriate policy. Industrial network analysis may be used for education or to inform policy decisions in this case.

2.4.3.4 Slow or limited reversibility of the environmental issue

One last barrier to sustainability is time. Even if strategies are implemented and properly managed, the expected improvement in environmental performance may take years to decades to fully come into effect. Despite a global ban on CFCs, for instance, the closure of the ozone hole is still progressing, decades after the bans had been deployed. The situation may be similar with greenhouse gas emission mitigation measures, though predictions on the consequences of greenhouse gas concentrations in the atmosphere vary. With global economic growth and the associated rise in consumption, time may well be a luxury commodity that industrial network and society cannot afford. Continued growth in consumption may also outweigh any improvement to be had from implemented sustainable development strategies. The lesson here is that sustainable development strategies should be deployed sooner, rather than later.

2.4.3.5 Limited agent cooperation

It is the norm in industrial networks that multiple parties have control over different parts of the network. If a strategy is to succeed, multiple network agents, such as government, consumers and a number of organisations with different perspectives, interests and management structures will have to cooperate (Wolf et al., 2005). However, in many cases the conditions making it either attractive for agents to cooperate or otherwise enabling agents to cooperate are not given. Barriers preventing the agents from *wanting to cooperate* are:

- Lack of knowledge about possible solutions, how these are to be implemented and the effect on the network, as discussed in section 2.4.3.
- Improvement opportunities are further not realised due to individual agent's organisational weaknesses, resistance to change, routine behaviour and risk aversion. "*Neither a real or hypothetical market is likely to generate sustainable outcomes. This is because in markets both households and firms tend to discount the future*" (Jacobs, 1995).
- Agents are focused on optimising the realm within their sphere of control. Examples of this include firms concerned with profit, decision-makers with short-term agendas, scientists with subspecialties, and households with material accumulation. A significant influence here is the behaviour of currently powerful actors who act to inhibit changes to current systems that would reduce their economic power (Pierson, 2000). "*The danger is that such local rationality taken in aggregate leads to global irrationality, to a pattern for the whole system that would have been chosen by no one.*" (Raskin et al., 1998).
- Cooperation is only entered into if the expected outcomes do not put the involved agents at a disadvantage. If this is not possible, some form of compensation or other incentive is required. Cooperation becomes increasingly challenging the more agents are involved, as the number of individual objectives increases and the possibility of conflict rises. Furthermore, cooperation requires trust, coordination, information has to be homogenised (Sterr and Ott, 2004).

If these barriers are overcome and agents signal their willingness to enter into cooperative relationships then the following barriers will still have to be overcome:

- Cooperation requires information sharing and processing. It may be unclear what information is needed and agents may also hold information back when they fear compromising their strategic benefit. They also have limited ability to handle large amounts of information effectively, a phenomenon known as bounded rationality (Kahneman, 2003; Simon, 1957). This also negatively affects technology diffusion and learning (DeCanio and Watkins, 1998). Even if necessary information is available, agents may not be aware of where to look for it or how to effectively interpret it.

- Chiu and Yong (2004) revealed a number of difficulties in EIP management. These problems include difficulty, in some cases, in being able to accurately measure the development and functioning of the EIP, lack of correct technology and know-how and insufficient management systems and practices.
- Agents may baulk at giving away information for fear of loss of competitive advantage. Even if cooperation is entered into, there may be miscommunication or misinterpretation about what information is necessary (Zhu and Cote, 2004) or difficulties in information dissemination (McIntyre, 1998). To date cooperation amongst different industrial network agents has been explored in supply chains, but here cooperation worked either because the companies were working towards a common goal, the relationship was mutually beneficial, or there was a dominant supply chain agent that could enforce its vision (Nilsson, 2001; Wilkinson and Young, 2002). Adequate mechanisms and approaches remain to be worked out. Third parties, such as government and regulatory agencies may need to come in to provide guidance, to mediate and coordinate and create incentives.

It was stated in Chapter 1 that agent behaviour would not be explicitly be included in industrial network analysis, as the analysis is intended to be prescriptive, i.e. it should provide insight into “best” or preferred network development. Yet agent perspectives should be kept in mind during the interpretation of analysis results to identify where and why agents may resist a certain strategy and resulting network development pathway. Outcomes of industrial network analysis could help overcome the barrier of agent opposition to cooperation by demonstrating possible benefit if the strategy is adopted.

2.5 USE OF POLICY INSTRUMENTS TO HELP OVERCOME BARRIERS

If strategies such as reintegration or substitution are possible, but for some reason unattractive, it may be necessary to use some form of leverage in an attempt to overcome these obstacles. Policy instruments are used by government to affect change on a large scale and are often used to promote sustainable development strategies in industry. These policy instruments can be used to overcome some of the barriers to sustainable development. The policies can be regulatory (“command-and-control”), economic or social/persuasive.

2.5.1 Regulatory Instruments

Regulatory instruments include standards that organisations have to comply with. In the case on non-compliance, they incur a penalty. There are four categories of standards (Barde, 1995):

- Ambient quality standards (e.g. maximum level of sulphur in air)
- Emissions or discharge standards (e.g. maximum output of SO_x by a facility)
- Process standards (e.g. obligatory installation of filters)
- Product standards (e.g. catalysts in cars)

These standards, collectively, can be used to influence performance at part of the industrial network: materials used, product specifications (and hence its production), production processes and waste treatment and disposal. Product standards may dictate increased material and energy efficiency, or design that facilitates recycling. Standards for recycling may prescribe a minimum take-back rate. While these standards can ensure that industrial network operates within acceptable bounds, it does not create incentive for further improvement. In this case, government can set standards that are stricter, but will only come into effect after a time-lag, giving industrial network the chance to develop cleaner products and processes. On a level of improvement, this fosters redesign and some degree of functional innovation.

2.5.2 Economic Instruments

Economic instruments affect the way companies and consumers make decisions by directly targeting costs (Baumol and Oates, 1988). They include, amongst others, taxes, charges, levies, subsidies, tradeable permits and property rights. Unlike the regulatory instruments which are very specific in the industrial network aspects they target, economic instruments leave agents considerable freedom in how they wish to respond to the changed prices. For instance, taxes on material and energy inputs could make recycling more attractive. This is also one reason why they are not used as much to stimulate environmental change (Opschoor and Turner, 1994). It is harder to predict the degree of success an economic policy will have, whereas with a regulatory policy this is known. Kandelaars (1999) recommended the use of the following four economic instruments for stimulating environmental change within a so-called material-production network, which is similar to an industrial network:

- Taxes, charges and levies
- Tradeable permits
- Subsidies
- Deposit-refund networks

A tax, charge or levy can be enforced payment for discharged pollutants or the associated environmental change (Barde, 1995). Taxes have three advantages: they create revenue for government, they provide incentive to reduce pollution and they can be used to some extent to cover the costs for abatement. The basis for taxes can often not be measured directly and in such cases proxies are used. For instance, the carbon content in fuel is the basis for a CO_2 tax.

Charges differ from taxes in that they are payments for services. Charges raise the price of products, but the revenue thus generated can be ear-marked for environmental, but also general purposes. In an industrial network, taxes and charges can be used to push for or penalise against the use of certain products or processes. A tax on certain raw materials can increase the use of secondary materials.

With the introduction of tradable permits, a government sets up an “optimal” amount of permits so that the total quantity of pollutants is restricted and the total costs of reaching that quantity is as low as possible. The idea was first published in Dales (Dales, 1968) and in an ideal case, the polluting companies that buy the permits will benefit while government will have no costs (Barde, 1995). Through trading, the market sets the price and adjusts to changes, such as number of participants, new technologies and inflation. The problem with these permits is setting the standard in a way that it achieves the environmental goal. To stay with the previous example, the national emission limits set for the first round of trading were too high, which resulted in a collapse of permit prices rendering the policy instrument ineffective. There are also problems with the initial allocation of the permits and monitoring trading and trading costs may affect the trade negatively (Stavins, 1995). The most topical example of tradeable permits would the trade of carbon credits which has commenced in the European Union to curb greenhouse gas emissions (EU, 2005). Like charges and taxes, tradeable permits can be used in industrial network sustainability analysis to penalise the use of, for instance, fossil fuels, encouraging the choice of energy efficient technology and use of renewables.

Subsidies are payments to producers or consumers that encourage them to choose a less environmentally damaging option. Subsides have a number of disadvantages: 1) They can be expensive for governments and 2) they may not reduce the emissions of a firm or an industrial network because new firms are encouraged to enter (Baumol and Oates, 1988). Subsidies also contravene the Polluter Pays Principle by paying a company for environmentally damaging acts (Bugge, 1996; OECD, 1972). Nevertheless, these types of incentives are becoming popular again, for example the use of tax reductions on environmentally friendly investments. Subsidies can be used in industrial networks to make new cleaner technology more attractive, or to encourage the use of more environmentally friendly products which would otherwise be considered expensive.

Deposit-refund networks are a combination of tax, i.e. the deposit, and subsidy, i.e. the refund. This makes a network financially neutral and it stimulates activities that would otherwise not be undertaken (Bohm, 1981). The deposit-refund network works in two ways: it discourages product use due to the increased price, then encourages recycling through the incentive of the subsidy given on return of the product. While deposit-refund networks are mostly used on the consumer, increasingly they are applied in industrial network to encourage the take back of harmful substances, such as heavy metals and sulphur. The material is bought when needed and returned for waste processing or export.

Economic incentives such as taxes and fees have been suggested by several authors in the IE literature, as these are seen as means to internalise environmental costs, if even the means (Ayers, 1991; Bey, 2001a; Frosch, 1992; Indrianti et al., 2006; Nordhaus, 1992; Tibbs, 1992). However, caution has been advised that economic instruments are not foolproof methods of encouraging companies and consumers to behave more environmentally responsibly (O'Rourke, 1996). In industrial network analysis, the effectiveness of economic instruments can only be assessed to some extent. If it is revealed during an economic assessment of an industrial network that certain technologies are too expensive, it may be checked at if available subsidies, or a new subsidy of the necessary magnitude, would make the technology feasible. Similarly, if a new environmentally sound product is unable to compete with a less environmentally friendly, but cheaper existing product, the analysis could deliver information on a tax rate on the existing product that would make the environmentally sound product more competitive. This would however not guarantee that the subsidy or tax would succeed in practice.

2.5.3 Social Instruments

Social, or persuasive, instruments attempt to change people’s behaviour by attempting to change their values, opinions or preferences. They include education and information, voluntary agreements, training, social pressure and negotiations (Kandelaars, 1999). Voluntary agreements can be defined as “*deals between government and industrial network, whereby an industrial network sector or group of individual corporations agrees to reach a certain environmental objectives within a defined time frame*” (Barde, 1995). The benefit of voluntary agreements is that they are flexible and that the companies themselves take responsibility. Knowledge and costs may be shared among companies. However, voluntary agreements are mostly entered into because the alternative is legislation or some other more stringent instrument. Many of the existing voluntary agreements are built around packaging take-back, such as the French Eco-*emballage* and the Dutch “packaging covenant” (Brisson, 1993).

While social instruments are useful tools to change behaviour in practice, it is difficult to estimate their take-up by consumers and assess their success in theory. Regulatory and economic standards are more easily captured as binding constraints on the industrial network or changing parameters in the underlying quantitative models. However, it would be difficult in the top-down, techno-economically focused approach used for the industrial network analysis proposed in his thesis to capture if, and to what extent, companies adhere to standards. For instance, a product standard dictating a level of recycled material use may involve a logistical challenge or reduced product quality. These are real-life implications that would not be captured by the industrial network analysis.

2.6 CONCLUSIONS

While the preceding discussion is generic, the insights can be used to identify and define the specific issues for a particular network. The issues will differ according to the location, type, size and performance of the facilities included and the materials handled, as well as the natural, socio-political, economic and regulatory environment in which the network operates. The industry's contribution to sustainable development strategies will therefore have to be tailored to the individual situation.

These strategies discussed in this chapter should be seen as guidelines as to what opportunities exist for improving performance, rather than adopting them as prescriptive, normative "shoulds" or being seen as desirable under any circumstances (Korhonen, 2007). They can be used individually or in combination and it has been recommended that analysis should encompass a wide consideration of strategies, rather than being focused primarily on one, such as waste management (Tudor et al., 2007). In either event, the strategies are likely to affect the network as a whole, either because cooperation from several or all concerned parties in the network is required, or due to a ripple effect if one entity in the network were to adopt a strategy, or if new entities would be introduced, existing ones eliminated, or new connections between entities added. The choice of strategies therefore significantly influences network structure and operation, i.e. what parts of the wider industrial system are included in the network boundary, how the entities operate and how the entities are linked. This will have to be considered during the industrial network analysis when determining the system boundary and network representation.

The next chapter will explore the object of analyses: Industrial networks. Chapter 3 delivers a characterisation of industrial networks and explores why and how these characteristics should be included in analysis.

3

CONSIDERING THE SYSTEM: INDUSTRIAL NETWORK CHARACTERISATION

3.1 INTRODUCTION

Where the previous chapter dealt with the context of the analysis, this chapter turns towards the object of analysis: industrial networks. The scope and configuration of an industrial network is influenced by the current connections of the facilities, but also by the environmental issues and consequently the strategies that have to be deployed to address these. Nevertheless, certain features are generic. These features are identified and discussed in this chapter. The characteristics refer to structural characteristics as well as behavioural characteristics. The aim of the characterisation is to

- to provide insight into industrial network structure and behaviour
- to highlight the influence of individual characteristics on network structure and operation. This includes the role such characteristics play in sustainable development, i.e. where and how changes could be applied to drive the network towards more sustainable practices.

This characterisation is to some extent influenced by the PSE and SCM literature. Aspects that these fields deem important to consider in analysis are included here, for instance the need to ensure a degree of flexibility to maintain robustness in a connected network in the face of disturbances (PSE), or the complexity of managing recycling streams to which an entire area of SCM called reverse logistics is dedicated.

3.2 STRUCTURAL CHARACTERISTICS

Structural characteristics refer to the physical nature of the network. This includes a description of the individual nodes as well as the links that exist between them, but also the network environment.

3.2.1 Nodes and Links

The basic constituents of an industrial network are nodes and links. Nodes represent the network components. The nodes of an industrial network encompass resource extraction, processing and refining, forming and assembly, use, disposal, as well as collection, recycling and reprocessing facilities. The majority of these nodes represent existing facilities, but the network can be extended by facilities proposed as part of an improvement strategy. By including new facilities the performance of the network can be assessed before and after to determine whether the addition has an overall economic, environmental and/or social benefit. Links represent the connections between the network components. The links represent the exchange of materials, but can also represent energy, monetary and information flows, which in turn form the background system to support the provision of products. Energy may however become part of the foreground system if it is a main or by-product of network activities.

3.2.2 Sources and Sinks

Networks dealing in materials exchange have distinct overall sources and sinks: These represent the origins and ultimate destinations of all materials flowing within a system. In Figure 3-1, sources are the “Harvesting/Mining raw materials” nodes, whereas system sinks include “Landfill/Losses/Dispersion”, as well as “Other network”. Typical sources are virgin raw material resources, secondary raw material stocks (such as recycled material) or imported goods. Sinks are landfills, export, or the sending of materials to some other process or system for use. In terms of lowered resource consumption, original sources (e.g. mines, oilfields) and ultimate sinks (e.g. landfill) of non-renewable material should be eliminated as far as possible to generate a closed cycle. In the case of renewable resources, the material consumption by the network should not exceed the rate at which it can be replenished. While such a number would be hard to fix, it would put a constraint on the network in terms of its material intake.

If these original sources and ultimate sinks are not directly in the network then the flow of material coming from, or going to, these nodes should be reduced as far as possible. This is in line with the strategies of dematerialisation and substitution and addresses the issues of waste disposal and excessive resource extraction.

3.2.3 Stocks

Stocks are the accumulation of materials and products within individual nodes. This accumulation occurs when more material enters than departs a node at a given time, in other words when there is a time delay between the time the material enters and departs. In the processing nodes small stocks of set size accumulate in the form of inventory that acts as a buffer against unexpected process disturbances. These stocks can, for instance, be drawn upon when raw material supply becomes interrupted briefly or when product demand temporarily increases. These stocks are important to ensure smooth day to day operations; however, the trend in industries is towards just in time (JIT) deliveries. Advances in software and information management have made it possible for many industries, such as the automobile industry, to receive components on the days that are needed, thereby making inventory largely redundant. While this approach leaves very little room for error, it provides significant cost savings as storage costs are avoided.

In strategic analysis where the time frames considered are much larger, these inventories will have less of an impact on network planning than the consumer stocks contained within the use phase (“Use/Consumer” in Figure 3-1). These stocks differ substantially from production inventories: The quantities are vast by comparison, widely distributed in millions of households, residence times are more variable, and material from consumer stocks is often released as heterogeneous waste streams. Depending on the nature of the product, products remain in the use phase for anything from a few days to several years or even decades before they are released through disposal. Elshkaki et al. (2005) characterise consumer stocks as being

- stocks of product, handled by users and producers (e.g. cathode ray tubes),
- stocks of materials, referring to the materials within the products (e.g. lead oxide) and
- stocks of substances, referring to the substances in the materials (e.g. lead).

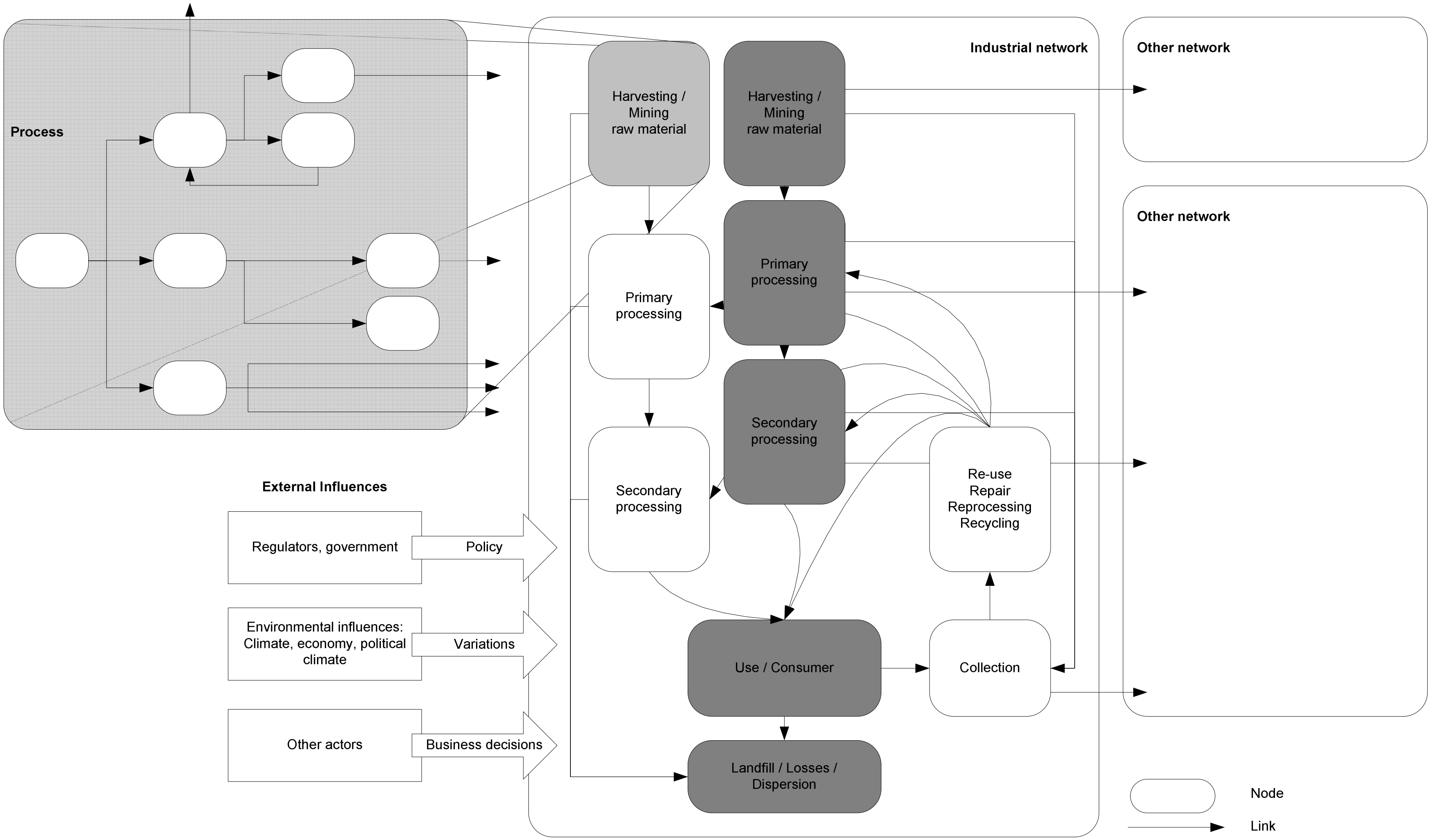


Figure 3-1 Generic outline of an industrial network. The network is connected through material and energy flows to other networks. Through information exchanges it also interacts with its wider environment. The dark grey elements represent a life-cycle (of which a supply-chain can be the entire thing or a sub-section), the lightly grey element a process system.

Consumer stocks represent a very important material resource alternative to virgin resources. For planning or reintegration strategies in networks it is therefore important to be able to estimate how much material becomes available at a given time and in what form. The quantity and quality (e.g. copper can be released in the form of wiring, piping or alloy form) of material released from the use phase is based on historical data capturing how much material entered the use phase, in what form and for how long it tends to be used. Numerous authors have captured consumer stocks in industrial system models to ascertain how much material is released and how much virgin material can be substituted (Elshkaki et al., 2005; Kleijn et al., 2000; van der Voet et al., 2002; van Schaik and Reuter, 2004).

3.2.4 Sub-systems

Each node in the industrial network represents another system: Individual facilities are composed of unit processes and the consumer market of multiple individual consumers (Figure 3-1). For industrial network analysis the processes used by the individual facilities are important to consider in terms of the technologies they use. These underlying processes within the facilities are optimised as far as possible with respect to efficiency and compliance to environmental standards. While environmental performance improvement on this level may be possible, this is unlikely to make a large difference on the industrial scale. Only major changes in operation or, for new facilities, the choice of different technologies and processes will have more significant effects on network performance. The underlying processes dictate constraints on nodal operation and determination of emissions, energy demand and water demand.

3.2.5 Reintegration Structures

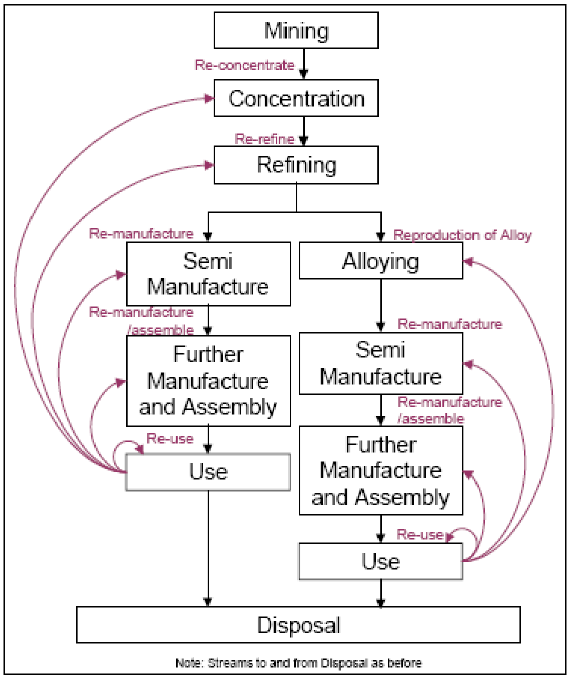
Reintegration structures, also called reverse supply chains in SCM, may already exist or be specifically introduced to an industrial network to enable material and energy reintegration, thereby substituting virgin raw materials and lowering waste disposal costs and volumes. The reintegration structure constitutes the “Collection” and “Recycling/Reprocessing/Re-use/Repair” nodes in Figure 3-1. Whether reintegration is a feasible option or an existing reintegration structure can be extended depends on

- the availability of suitable waste resource, i.e. waste stocks, by-product or waste streams
- the existence of receivers for the waste
- the accessibility of the waste, in other words is it easily collected and transported
- the quality of the waste, i.e. the number and type of materials, and the concentration and separability of the material of interest
- the quality of the material in the waste stream, i.e. the degree of degradation or contamination

- the technology specifications of waste receiving processes, i.e. the constraints on quality and quantity the facilities can accept.

Even if a waste is available that contains useful material, it may be so geographically dispersed that collection could be too costly, time and energy intensive. Reintegration may also not be feasible if the material of interest is contained in a heterogeneous waste stream which requires a significant investment and effort to enable separation. For instance, in the case of metals the concentration of the useful constituents in a stream affects the viability of recycling (Johnson et al., 2007). If availability and accessibility fail to be issues then it is the quality of the waste and the material properties that influence the degree of reprocessing necessary. This includes their state of deterioration and their constituent material properties. The greater the state of deterioration, which can be related to the relative age (i.e. retention in the use phase) of the product, the more reprocessing will be necessary to restore functionality. Thus highly degraded products may only be suitable for recycling to a lower specification application, whereas products that are in good condition can be repaired or re-used.

How the material properties impact reintegration is illustrated by an example in Figure 3-2 (PWC, 2001). During alloying the pure metal, for instance copper, is mixed with another metal, such as zinc, to produce an alloy, in this case brass. Once this mixing has taken place it is practically impossible to reverse the process, to separate the alloying metal and go back to pure copper and zinc. It is therefore impossible to recycle the alloyed metal be re-concentrating or re-refining it. Recycled copper can, however, be used again to produce new copper products or it can be alloyed.



Note: Streams to and from Disposal as before

Figure 3-2 Illustration of difference in the degree of reintegration possible in the supply chains of pure and alloyed metals (Source: PWC (2001))

The processes represented by any given node have certain requirements of their raw materials. Should a material stream fail to meet the necessary specifications, it is unsuitable for use and will be rejected by that particular node (Mellor et al., 2002). This is an important consideration especially in the presence of recycle structures, which handle material of highly variable quality[7]. What properties are relevant to the use, or reuse, of materials depends on the processes involved, and the desired functionality of the products. Plastic bottles, for instance, should have a certain clarity and strength, and these can only be achieved if the bottle manufacturing process is supplied with raw materials of sufficient quality.

Reintegration structures can be classified as forming either closed loop or open loop (ISO 14041). The former indicates that the material is reintegrated within the original supply chain that delivered the product. If the material is instead sent to be reintegrated in another supply chain, it forms an open loop. The latter is commonly used in those cases where material quality requirements of the original supply chain stages cannot be met by the properties of the waste material, or where reprocessing is too costly or energy intensive. The material may nevertheless still be valuable enough to make it feasible to send them to some other, lower specification application requiring these materials (Clift and Wright, 2000).

3.2.6 Material Properties

The properties of material and products circulating in a network are important for two reasons: Firstly, if a material is toxic or rare it is of interest to minimise the use of this material or to substitute it with another raw material. The same is true if the material has an undesired impact associated with it, for instance if it is obtained through untenable labour practices. Secondly, material properties play a crucial role in the reintegration of materials and products. The properties of a material or product will vary according to the location within the network. Some material properties are inherent to the material, for instance electrical conductivity or toxicity, while others are influenced by the processes they undergo. With a view towards reintegration, the inherent properties of materials could, for instance, be classified as being either atomic (e.g. metals), molecular (e.g. chemicals), or structural (e.g. wood, some plastics and ceramics) (Five Winds International, 2001). Atomic materials, such as copper, can be fairly easily and theoretically indefinitely recycled, whereas structural materials, such as wood, can only be reprocessed a limited number of times in a very limited number of ways as the material degrades irreversibly with each reprocessing step. Molecular materials can be reprocessed more than structural materials, but some contamination or breakdown will occur that no amount of effort or energy input will be able to avoid (Five Winds International, 2001).

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[7] This is not applicable to recycle streams on a process level. In these cases the recycle amount and composition are well known and controlled.

Once a stream fails to meet the acceptance criteria of a certain node, the whole stream can be rejected (Mellor et al., 2002). Should material fail to be accepted by one node, it may still be reintegrated somewhere else. The more degraded a material or product is, the further up in the initial manufacturing stages of the system it will have to be reintegrated, as it will require more reprocessing: High quality secondary materials can be reused; low grade materials will have to be recycled. What properties are relevant to the use, or reuse, of materials depends on the processes involved, and the desired functionality of the products. Plastic bottles, for instance, should have a certain clarity and strength, and these can only be achieved if the raw material does not introduce too many contaminants.

3.2.7 System Boundary

While industrial networks are connected directly or indirectly to countless other systems, technical, natural and social, boundaries must be drawn between the technological system and nature and between the network and other technological systems to break the scope of the problem to a manageable size (Tillman et al., 1994). An industrial network has been defined, in its simplest form, as a set of linked components. Pertinent to the analysis is a consideration of:

- resources used
- products delivered, and functionality desired of products (this is important for consideration of substitution)
- Technologies used and additional technologies required or available.
- The properties of the materials circulated. This is an important factor in determining recycling opportunities.

The network boundary and how it is determined, and what should be included, is driven by the network in question as well as the strategies to be explored. This will be discussed in more detail in section 3.4, where the different types of networks are introduced. However, the industrial network nodes constitute the entire life-cycle of products that are circulating within the network. The scope of the industrial network analysis should include the entire life-cycle of the product/s it is looking at. The life-cycle boundary encompasses, to borrow from the ISO 14041 standard (ISO, 1998):

- material or energy entering the system being studied, which has been drawn from the environment without previous human transformation.
- material or energy leaving the system being studied, which is discarded into the environment without subsequent human transformation.

To mitigate the impacts associated with a product, intervention has to be addressed at the appropriate point in the life-cycle. The use phase cannot be ignored as the demand for products originating from this node is the driver of the network. At the same time the use phase is a store of materials and a source of waste (see section 3.2.3 on stocks). The life-cycle is also important to consider as an intervention at one point will have repercussions for the remaining elements in the chain.

At the same time it has to be kept in mind that the broader and more inclusive the network boundary, the less detailed the consideration of nodes and flows can be. For instance, a network encompassing international copper flows could be mapped, but the technology representation would have to be aggregated and abstracted. The delivered information would subsequently not be able to account for the economic or socio-political situation of particular facilities or for their properties of individual material streams. Neither would it be possible to assess opportunities for improving environmental performance that are available and suited to a particular facility or a material stream or resource. While strategies could be developed on the basis of such information, it would have to be robust strategies that fit to a wide variety of situations. Tailoring strategies to particular situations would in this case not be possible.

3.2.8 Industrial Network Environment

Industrial systems are "open" systems, in continuous interaction with their environment, as illustrated by the links across the system boundary in Figure 3-1. This network "environment" encompasses multiple aspects, including the industrial, economic, natural, socio-political and regulatory environment. Not all of the environmental influences can, or should be explicitly expressed in a quantitative analysis. However, it is important that these factors are elicited and, if deemed important or of significant impact on the success or failure of a strategy, at least qualitatively considered during industrial network analysis. A solution that may work for a network in one country may not work for a similar network in another location due to the changed conditions.

3.2.8.1 Technical environment

Any type of industrial network represents a sub-system within a wider regional, national and global industry and is in direct interaction with other networks. Connections therefore exist to other industrial networks in the form of material, energy and information exchanges, but also through business relationships. Korhonen (2001a) mentions the locality of an industrial system and gradual change in the technical environment playing a crucial role in driving industrial networks towards more sustainable practices. This is because the industrial environment may, for instance, supply reintegration options for wastes, or it in turn may be the source of alternative raw materials. *The industrial environment is therefore primarily of interest in industrial network analysis in its contribution towards sustainable development strategies*. However, the local industrial environment may also be a source of competition for resources and products. This has to be considered, at least qualitatively, when evaluating strategies that would recommend the switch to alternative raw materials, or when launching new or adapted products. At this point the economic environment comes into play.

3.2.8.2 Economic environment

The economic environment dictates raw material and product prices and market demand for final consumer products, the presence of competitors for resources as well as products. This is also a dynamic environment, with prices of materials constantly changing according to supply and demand. The economic environment, with its costs of technologies and raw materials and prices of products strongly *affects the attractiveness of pursuing sustainable development*. While providing “green” products may mean a higher price can be asked for the product (which would encourage companies to adopt sustainable development), high costs of new technologies may be a barrier. In Europe for instance, carbon trading and capping has been instituted which is intended to affect the cost of operation, driving companies to adopt cleaner technologies in order to avoid costs of carbon emissions. Developing nations are exempt, even if they are encouraged to drive development in such a way to reduce or avoid impacts through clean development mechanisms (CDM). This example also serves to make an important point: While carbon trading has an affect on the economic environment, it originated from the regulatory environment, which will be discussed in 3.2.8.5. This demonstrates that the different aspects of the network environment are also interrelated. This interrelatedness contributes to the complexity of the sustainable development, as one thing always affects another.

3.2.8.3 Natural environment

The natural environment interfaces with the industrial network as the provider of resources and the receiver of emissions and wastes. The natural environment may be negatively affected by industrial network activity, giving rise to one or more of the sustainable development issues identified in Chapter 2, such as overexploitation of a resource or release of harmful substances. An issue always exists if an industrial activity has environmental impact on a global scale, or if the activity has a negative local impact irrespective of the state of the particular local environment. In these cases, the activity always creates an issue. Emissions of greenhouse gases, for instance, impact global climate and are therefore an issue irrespective of the location of the network. The release of heavy metals such as mercury on the other hand should be avoided under any circumstances as the metals are toxic no matter where they are released. If, and to what extent, an industrial practise creates an issue may vary with location. In arid countries such as Australia for example, management of the scarce water sources may receive considerable attention, with government intervention encouraging the increased use of recycled water, or the expensive investment in desalination or drilling for artesian water, whereas in countries with abundant water resources, such as

Canada or the UK, water resources are generally abundant and consumption is regarded as much less of an issue. *Whether an issue exists depends on the nature of the activity of an industrial network, but also on the state of the (local) natural environment*.

Furthermore, even if this interaction with the environment would not create environmental issues, *the natural environment determines the quality and availability of virgin resource stocks*, which industrial networks process into valuable products, thereby generating revenue. How these resources are provided to industrial networks influences network structure, operation and performance, now and in the future. Resources may be locally situated or far removed, their stock may be growing, diminishing or seasonal, and they may be easy or difficult to access. While some resources are abundant, some are scarce or diminishing and therefore need to be managed more carefully. Some resources, like metals, coal and oil, are transported cost-effectively all over the world, whereas many renewable resources may be less flexible. Other natural resources are only locally or regionally available, e.g. renewable energy sources like solar and wind, or they may only be feasible to process locally. For example, in the second case study in this thesis (Chapter 8), the low bulk density of bagasse, a fibrous residue from the sugar industry, makes it uneconomical to transport this potential resource over long distances.

3.2.8.4 Socio-political environment

The socio-political environment refers to the interests of society in which the industrial network is embedded and the government which may attempt to influence its operation through policy and regulation. In some cases, society and its (elected) government may desire to protect the natural environment. Social awareness or perception of issues may contribute towards adopted practices. For instance, the current global concern about climate change in the media means that the public has become aware of the contribution of fossil fuels to the problem. In Germany, this has led to the public opposing the building of new coal fired power stations. However, society and government also have social and economic interests that often conflict with environmental protection. Particularly in developing countries, the government has the obligation to provide a “good” standard of living to its citizens, meaning job opportunities, health, education, access to water and electricity. This is a declared development goal of the Johannesburg Earth summit (UN, 2002a). In first world countries, there may be an interest to drive economic growth and wealth.

3.2.8.5 Regulatory environment

The regulatory environment encompasses the policies and regulations acting on the network. As discussed in the previous chapter in section 2.5, the regulatory frameworks may encourage sustainable development by penalising environmentally harmful practices (e.g. fines for not adhering to standards) and/or by providing incentives to abandon harmful practices in favour of better performing alternatives (e.g. subsidies and taxes). However, they may also act as barriers if they are mismatched or if government is too controlling (section 2.4.3.2).

3.3 BEHAVIOURAL CHARACTERISTICS

The behavioural characteristics refer to those network features that determine how the network forms, develops and operates. Consequently they exert an influence on the structural characteristics of the network. In terms of industrial network analysis, these characteristics play vital roles in how strategies can be implemented and the support or hindrance their implementation may receive.

3.3.1 Drivers for Network Formation and Transformation

Drivers are the major forces behind network formation and transformation. They may exert an influence on the network that either supports or hinders sustainable development of an industrial network. These drivers may be either internal, i.e. originate from within the network, or external, i.e. being exerted on the network from outside the system boundary.

Internal drivers are the visions of the network agents and how they wish to operate and position themselves and who they engage with in the network. Whether or not a link between two nodes in a network is formed is not merely dependent on the technical and financial feasibility of such a move, but also on the desire of the concerned agents to enter into the relationship.

External drivers include the influences from the network environment: Public pressure, government regulations and policies, and the preferences and goals of other stakeholders that are not directly part of the industrial network. However, the major driver in industry is arguably the demand for products, as without the demand for a final product the entire products life-cycle would not exist. Demand is influenced by significant variables such as price compared to the process closest substitute and level of overall economic activity (Tiltone, 1990), can be represented by gross domestic product. Variables that influence it are population growth, technical development and welfare. Technology may influence it by generating alternatives or changes to product design.

Insights into the effect of drivers are useful to determine what effect they have on industrial network development and how this effect can be promoted, altered or avoided. If possible, new drivers, such as additional policies, could be initiated in an attempt to encourage the network agents to, individually or collectively, adopt the sustainable development strategies identified in Chapter 2. As agent behaviour is not explicitly considered in this thesis, the policy instruments that can be assessed are regulatory and economic instruments (section 2.5).

3.3.2 Dynamic Nature of Networks

The drivers for the network, the network environment, and the network itself, such as its technologies or its facilities, are likely to change during the life-time of the network. Therefore networks have to adapt to internal as well as external changes, and show dynamic, i.e. time-dependent behaviour. Important dynamics include those surrounding the build up of stocks in the use phase (Elshkaki et al., 2004; Kleijn et al., 2000; van der Voet et al., 2002; van Schaik et al., 2002b; Verhoef, 2004), which influences the resulting quality and quantity of materials released.

Another time-dependent development is so-called technology learning. It is widely accepted that the costs of a process reduce as more units are built and experience accumulates. A learning curve may consequently be observed, which translates to a 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. Another common assumption is that future development will enable a further reduction of environmental impacts. Pehnt (2006) suggested that, for renewable energy generators, the following factors may enable such a development, such as progress with respect to technical parameters of energy converters, in particular, improved efficiency, emissions characteristics, increased lifetime, etc.; advances with regard to the production process of energy converters and fuels; and advances with regard to "external" services originating from conventional energy and transport systems, for instance, improved electricity or process heat supply for system production and ecologically optimized transport systems for fuel transportation (Pehnt, 2006).

Expected future developments can either stem from the network environment, or from the decisions that are to be evaluated as part of the networks analysis. The former would include factors such as changes in the political, environmental and economic climate in which the network is embedded. The latter concerns policies and regulations and new technological developments or other innovations that are proposed *as part of the analysis*. Depending on the industrial network and analysis context, policies and new technologies could, however, also be generated in the *network environment,* influencing the industrial network externally. Either of these types of future developments would have a significant effect on the network performance. These developments over time and thus have to be accounted for, especially in light of the irreversibility of many decisions.

Some of the future events that may occur *within the network* are:

- New products being developed that compete for resources.
- New markets open up for the product(s) and waste(s), creating added revenue and/or added competition.
- New technologies are developed that may make previously impossible, impractical, or costly processes feasible.
- A currently used resource or product may be made redundant by substitution with other resources, products or services.
- New competitors entering the network, demanding a share of the resources and/or a share of the market.
- Individual companies leave a network (e.g. due to financial collapse), necessitating a restructuring of the network.

Future events that impact on the network, but originate in *the network environment* are

- The introduction of new policy and legislation.
- Changes in the political or economic climate (where the political climate may influence the economic climate and vice versa).
- Changes in the social climate, influencing type and degree of demand for products.
- Changes in the weather, which may affect harvests and operations. Already global warming is increasingly driving the push for non-coal and oil based energies.

Estimates of future trends, such as the costs/prices or resources can be based on historic data, as demonstrated in (Dempster et al., 2000; Devadas, 2001). There is significant uncertainty associated with future developments, as these are influenced by too many factors and guided by interactions too complex to allow exact predictions. This uncertainty has to be considered in industrial network analysis to ensure that any recommended outcomes would be robust, i.e. are likely to deliver “good” performance in the face of the anticipated realisations of the future. The topic of uncertainty is covered in more detail in Chapter 6, where sources of uncertainty in industrial networks are discussed, including future uncertainty, and how this may be handled in industrial network analysis to ensure robust outcomes.

3.3.3 Robustness of Industrial Networks

The increased integration of material flows between industrial facilities, for instance through increased recycling or waste mining, means that more industries become more closely connected and interdependent. This raises issues of network stability. Greater connectivity increases the chances of disturbances, such as process interruptions spreading throughout large sections, or even the entire network.

At this stage structural and functional robustness have to be differentiated: structural robustness implies that the network maintains its structure under different conditions. Functional robustness means that the network continues to deliver the desired serves or products, but it would be free to change its structure in order to do so. For industrial network analysis, the latter is the more important. Structural robustness is more likely a barrier to sustainable development rather than a desirable attribute.

If one of the main enterprises would leave the network or would look elsewhere for its materials or products, the entire network would be affected (Tudor et al., 2007). As an example of a specific response to this phenomenon, the Guitang Group which operates a sugar refinery in China as part of an eco-industrial park, sought to reduce this problem by incorporating companies that can act as alternatives, whereby if one experienced problems then another would compensate (Zhu and Cote, 2004). Another strategy could be to incorporate diverse suppliers and resources, thereby enabling the network to adapt to change and recover more quickly (Korhonen, 2001b). This would require an even greater degree of cooperation as more companies become involved, but at the same time this increased participation would further contribute to sustainable development by closing material cycles amongst more facilities[8]. However, too much diversity can lead to conflicting preferences, values, interests and wants (Korhonen and Sankin, 2005) as well as higher transaction costs in the establishment of relationships. This highlights the importance of communication between the involved agents (Korhonen, 2001b).

3.4 INDUSTRIAL NETWORK TYPES

Industrial networks come in a variety of forms, all featuring the above characteristics discussed in the previous two sections. As a result it is seen as desirable that industrial network analysis is flexible in regards to the network it captures. The view of the network, i.e. the network boundary and structure are primarily dependent on the issues to be addressed. Four general network types van be identified:

- Region-based
- Product-based
- Resource-based
- Agreements-oriented.

In IE, industrial systems are classified as regional or product-based systems, also referred to as symbiosis and life-cycle views of the system (Boons and Baas, 1997; Korhonen, 2002; Lowe, 1997; Seager and Theis, 2002), and Van der Voet et al. (1999) put forth the concept of agreement-based systems. The

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[8] By the same logic the chance of waste energy integration would increase, but this is dependent on the facilities being in close regional proximity of each other.

resource-based view is a novel concept introduced in this thesis. It is inspired by the life-cycle perspective, but shifts the focus from network output (product) to input (resource). Which of these network views is adopted for the analysis of a particular network is determined by the characteristics of the network, such as existing links, but primarily by the issues and the resulting strategies to be assessed. The network view facilitates the drawing of the system boundary, by indicating which sections of the wider industrial system are included explicitly in the analysis.

The **regional view** aligns its view of the network with that of industrial symbiosis, which focuses on integration of materials and energy in specific industrial estates or eco-industrial parks or in a region (Chertow, 2000, 2007). An example of such an industrial network is given in Figure 3-3. Well-known examples of industrial symbiosis include Kalundborg in Denmark (Jacobsen, 2006; Jacobsen and Anderberg, 2005) and Kwinana and Gladstone in Australia (van Beers et al., 2007). The emphasis is on the advantages of co-locating industry (Chertow and Lombardi, 2005; Desrochers, 2004; Krugman, 1991; Porter, 1998). Due to transport consideration, potential alternative uses would be preferably in the same region. The benefit of geographical proximity can stimulate the formation of eco-industrial parks, where a variety of different processes, using different resources and generating different products, can exchange heat, waste and by-products as alternative resources. This has the benefit that heat, which cannot efficiently be captured and transported long distances, and cheap secondary materials that are not worth the transport costs, can find alternative uses that would otherwise not be available. The only requirement is that process requirements match the specifications of the alternative resources available.

The other common system view in IE is the product-based view**. An example of this is illustrated in**

Figure 3-4Figure 3-4. The boundaries in this case encompass the entire life of the product, from cradle to grave. The emphasis tends to be on material cycling (Seager and Theis, 2002). Where the regional or industrial system view tends, in the IE literature, to be focused exclusively on industrial entities, the life-cycle perspective pays attention to the role of the users in driving system behaviour and creating impacts (see Rejeski (1997), Anderberg (1998), Bey (2001b), Hertwich (2005a)). The consumption can be spread over a wide geographical area. This dispersion of materials, and the subsequent potential collection, can be costly and energy intensive (Korhonen, 2002). The aim in product-based approaches is to trace the use of virgin inputs, material and energy (as well as the generation of waste and emission outputs) throughout the product's life. Therefore, consumption and possibly related recovery and recycling are also taken into account, although these activities may take place far away from the original place of production. This view is adopted in life-cycle management and life-cycle analysis (LCA), but also aligns itself with supply chains (Seuring, 2004a). This is discussed in more detail in Chapter 4.

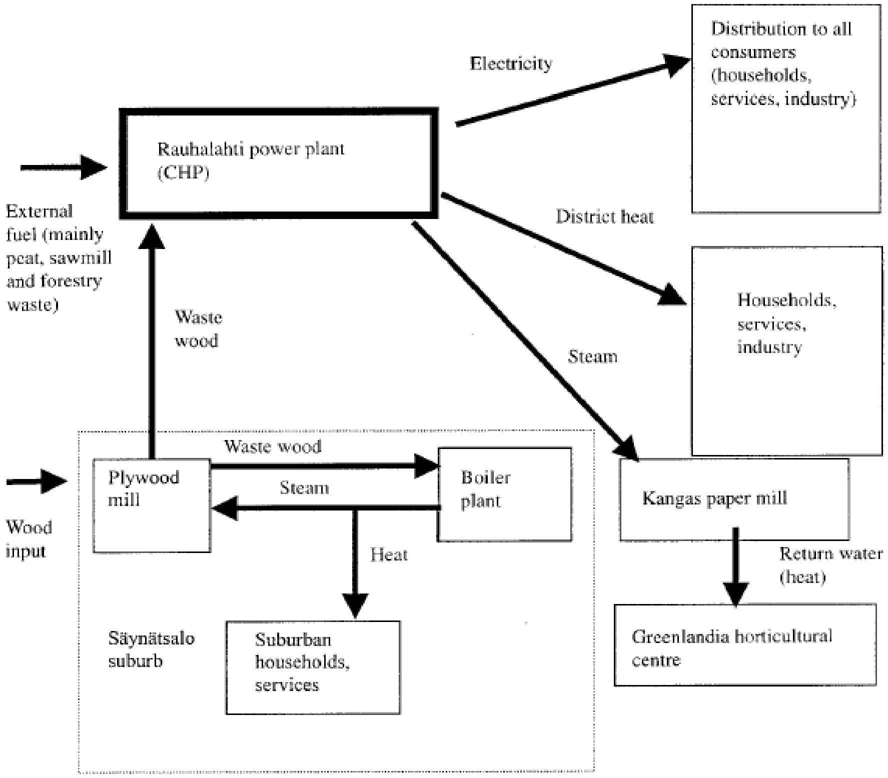

Figure 3-3 Example of region-based industrial network: Jyväskylä industrial ecosystem (Source: Korhonen et al. (1999))

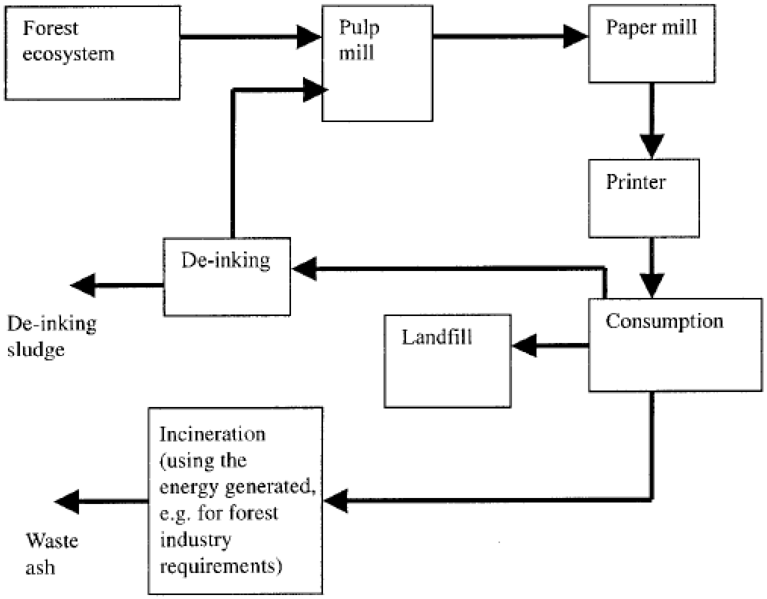

Figure 3-4 Example of a product-based industrial network: Life cycle of paper (Source: Korhonen (2002))

The regional and product-based views can be extended by a **resource based-view**. The resource-based view would be adopted if the main issue identified in a network is the use of non-renewables or over-exploitation of renewables. The resource-based industrial networks are defined on the basis of the products that can originate from a particular resource. This configuration is particularly suitable in the assessment of reducing use of non-renewables, and reducing overexploitation of renewables through reintegration: As the associated supply chains use the same resource they may be the most suitable destinations for reintegration some wastes and discarded products. If new product supply chains are to be added to an existing resource-based industrial network, it may be worthwhile checking if this is the best way to use the resource, or if the resource is even the best one to use for the product in question. This approach is common to material flow analysis (MFA), where specific resource flows are tracked through the economy to determine their fate and the location of stocks. This too will be discussed in more detail in Chapter 4.

A fourth system type is the **agreement-oriented system** (Van der Voet et al., 1999). In this case the system is defined by the business relationships amongst all agents that have been put in place, or will be put in place, as part of environmental management strategies. Due to the material (and energy) focus of industrial network analysis, an industrial network would not be considered solely on the basis of its business relationships. The agreement-oriented system view can, however, be used in conjunction with one of the above system views, to consider how the underlying business relationships influence network planning. For instance, existing contracts between suppliers and manufacturers would prevent a facility from quickly switching to a new raw material source.

These four distinct network types are by no means mutually exclusive. Depending on the particulars of the network under consideration and the strategies identified, the network boundary and structure may exhibit features of two or more of the above network types. For instance, two product life-cycles that are based on the same resource may be included in the network boundary because it is expected that material integration between these two life-cycles is both beneficial but also easier due to similar raw material requirements and this is an approach taken for the case study in Chapter 7. Alternatively, the approaches could be used separately on the same problem. The product-based approach could serve as an inventory tool in conjunction with the region-based approach (Korhonen, 2002). However, while the approaches can be complementary it has to be kept in mind that when two or more approaches are adopted as each other's substitute, they may support conflicting decisions for environmental policy and management (Korhonen, 2002). This may create difficulties in the identification of sustainable development strategies. It may therefore be best to expand the system boundary to combine network views in order to determine strategy, or strategies, that manage to address the issues in an overall acceptable manner.

3.5 CONCLUSIONS

The characterisation of industrial networks provided an insight into industrial networks, their structure and behaviour. The industrial network characteristics thereby supply a foundation for industrial networks analysis. With a detailed understanding of the individual characteristics it is possible to determine the source of issues, the means available to address them, and the barriers that exist in this regard. For instance, consumer stocks represent alternative sources of materials. Tapping into this stock is attractive if the virgin resources from the source are either scarce or incur a higher impact than recycling of the post-consumer waste. Unless reintegration structures already exist, these have to be added to the network to exploit the alternative resources. However, this reliance on waste may be opposed by some agents in the network or the robustness of a network may be compromised if the release of these stocks is unpredictable or variable and therefore unreliable.

In many cases there is also an overlap between characteristics. For instance, many of the drivers, such as policies and stakeholder perspectives, originate from the network environment, and market demand fluctuations influence the dynamics of material flows and stock accumulation. Network characteristics consequently cannot, or should not be viewed in isolation. If one characteristic changes, others may be affected that potentially also influence network development. Ignoring this interconnection could have negative implications for the reliability of network analysis outcomes. Industrial network analysis therefore aims to take a holistic view of the network to ensure that as many of these characteristics as possible influencing the success or failure of a sustainable development strategy are considered.

Chapter 2 and 3 have provided the foundation for industrial network analysis by discussing the context, namely sustainable development, and the subject of the proposed analysis, the industrial network. Chapter 4 will move on to 1) a review of existing approaches used in IE to address sustainable development issues and 2) a review of analysis approaches and how these capture industrial systems from the fields of PSE and SCM. The findings of this review contribute to the development of the industrial network analysis methodology, which is the subject of Chapter 5 and 6.

4

ANALYTICAL TOOLS FOR INDUSTRIAL NETWORKS

4.1 INTRODUCTION

This chapter constitutes two parts: The purpose of the first part is to review the existing analytical tools used within the field of IE and to critique these in regards to the four issues discussed in Chapter 1. These included lacking consideration of:

- system environment and contextual complexity
- dynamic nature of the system and its environment
- economic and social impacts
- uncertainty.

In other words, the tools are critiqued with regards to their ability to explicitly consider the industrial network context and its intangible or qualitative features, be able to handle dynamics and multiple objectives, to allow a simultaneous consideration of economic and social impacts in addition to environmental ones, as well as the extent to which this is done. This critique serves two purposes:

1. To show the gaps or shortfalls in current analysis that the industrial network analysis proposed in this thesis aims to address.

2. To identify which of the existing analysis tools, or what features of these tools, are desirable for industrial network analysis and can be incorporated.

Which tools are chosen as a basis for industrial network analysis, or to contribute to industrial network analysis, depends on the extent to which the existing tools used in IE are able to accommodate the identified issues, be able to explore any of the issues in Chapter 2, and include the network characteristics discussed in Chapter 3. Furthermore it should be flexible with regards to the network it captures and be able to capture the characteristics in Chapter 3, either qualitatively or quantitatively.

The second part of this chapter introduces the industrial systems research fields of PSE and SCM. As mature research fields with a focus on the practical issues of managing and planning industrial systems, these fields yield approaches to strategic network planning and design and associated tools that further contribute to industrial network analysis. Special attention is paid to how these fields deal with dynamics, uncertainties and the capture of multiple criteria. In addition to the synthesis of tools resulting from the review of the existing environmental analysis tools, the contribution from PSE and SCM presents the major contribution of this thesis.

4.2 ANALYSIS TOOLS IN IE

A number of analytical tools have been developed for the purpose of addressing, primarily environmental, sustainable development issues in industry. Some of the commonly used analytical tools for environmental assessment are (Wrisberg and Udo de Haes, 2002):

- cost benefit analysis (CBA)
- cumulative energy requirement analysis (CERA)
- life cycle costing (LCC)
- life cycle analysis (LCA)
- environmental input-output analysis (env I/O)
- environmental risk assessment (ERA), related to environmental risk assessment (EIA)
- material input per unit of service (MIPS)
- material flow analysis (MFA)
- multi-criteria decision analysis (MCDA).

A brief summary of these tools is given in Table 4-1. Of these tools, the most commonly used in IE literature are LCA, I/O and MFA, with LCA seeming to be the most popular in terms of publication number (see Table 4-1).

Table 4-1 Analytical Tools (adopted from Wrisberg and Udo de Haes, 2002)

FRAMEWORK	DESCRIPTION	NUMBER OF PUBLICATIONS
Cost Benefit Analysis (CBA)	CBA expresses all impacts of a planned activity in terms of money, but from a social rather than an organisation's point of view (Wrisberg and Udo de Haes, 2002). Its application is very broad. What and how environmental indicators are converted into monetary terms depends to a large extent on the priorities of the decision-maker.	12
Cumulative Energy Requirements Analysis (CERA)	Comparable to materials input per unit of service (MIPS) and life cycle assessment (LCA), CERA assesses all the primary energy, or energy equivalents in the case of materials, used to deliver a product or service. The entire life of the service or product is considered: production, use and recycling or disposal.	0
Environmental Input-Output Analysis (env. I/O)	More an economic tool, I/O attempts to analyse all the flows within a (national) economy. Environmental Input-Output Analysis focuses on materials consumed, and products and wastes released by industries, and should indicate how industries are interlinked.	141
Environmental Risk Assessment (ERA)	ERA addresses the estimated environmental threat associated with a development, be this the introduction of new technologies, products, or activities. Where environmental impact assessment (EIA) is predominately concerned with identifying and addressing issues, ERA enumerates the likelihood and environmental or financial cost of an environmental impact.	5 (+16 for EIA)
Life-Cycle Costing (LCC)	LCC estimates all the costs, both internal and external, incurred by a product or process over its entire life time. The inclusion of external cost is unique to this framework, as most external costs do not directly impact the company.	6
Life-Cycle Assessment (LCA)	LCA can be combined with many of the other tools listed here (Azapagic and Clift, 1999c). LCA is the application of the LCM concept. It accounts for all the significant environmental impacts, both quantitative and qualitative, that a specific product or process may have during its entire lifetime, from cradle to grave (Azapagic, 1999). This information can show the greatest areas of impact which should be addressed for improvements to be most effective	144
Material Flow Analysis (MFA)	MFA analyses the stocks and flows of certain bulk materials and links those to the flows and ultimate fates of associated products, by-products and waste streams. MFA is usually performed for a specific geographical region, but it can also be performed on a plant or company level. MFA can involve simple mass balancing, or it can be a full dynamic analysis of stocks and flows over an extended period of time (Kleijn et al., 2000). A variation on this is substance flow analysis (SFA) which focuses on certain constituents of materials, i.e. specific substances or groups of substances.	51 (+16 for SFA)
Material Input per Unit of Service (MIPS)	MIPS is an indicator that shows how much material is required to deliver a certain product or service. The material input includes all the resources extracted from nature to deliver the product or service during its entire life-cycle. This includes production, use and recycling (Ritthoff et al., 2002).	2
Multi-criteria Decision Analysis (MCDA)	MCDA does not necessarily focus exclusively on environmental issues. In actual fact it is not in itself a tool, but rather it encompasses a number of tools. It simultaneous considers a range of economic, environmental and social issues and examines the performance of a system based on those criteria. The issues can be measured by both qualitative as well as quantitative indictors. MCDA does not give definite answers on how to tackle a problem, as the simultaneous consideration of multiple objectives often means that improvement in one area will often result in the deterioration of another. Stakeholder opinion plays an important role, as the best course of action is decided by a consideration of the trade-offs involved among the objectives, as well as the prioritisation of the objectives.	7 (incl, multi-criteria decision making, multi-criteria analysis)

The number of publications was determined by a literature search in the Compendex database. The search terms used were "industrial ecology" and the respective tool name (spelled out and acronym), and the number of hits recorded. Consequently, LCA, I/O and MFA will receive greater attention in the following critique. The tools in Table 4-1 are critiqued below with respect to their ability to:

- Provide a structured, transparent approach to considering the system environment and the context of the sustainable development issue in a particular case.
- Consider the dynamic nature of the system and its environment
- Consider, or are able to accommodate, economic and social impacts
- Consider, or are able to consider, uncertainty.

4.2.1 Consideration of System Environment and Problem Context

While IE prides itself on extending its view past the individual organisation to consider the system in which organisations interact, it is important to note that industrial systems are "open", in continuous interaction with their environment. The system environment has a significant influence on any system analysis. Firstly, it provides a context for the particular problem, i.e. the system and its associated environmental issues. Secondly, as the discussion in Chapter 3 in relation to industrial networks showed, many of the drivers and constraints acting upon the industrial system, thereby influencing its structure behaviour and development, originate from the economic, technical, natural and socio-political environment. These "environmental" drivers may also be what inspires a systems analysis in the first place. The network environment therefore influences how sustainable development issues are viewed, what opportunities are identified to address these issues and which are deemed preferable.

The analysis tools in Table 4-1 all have specific guidelines on how ecological environmental issues in an industrial system should be approached, but most do not provide guidance as to explore if, how, or to what extent the system environment may influence the analysis, and thereby, the interpretation of the findings. It would therefore be beneficial to a) elicit the particular environmental influences and their effects on the system in order to b) capture them, qualitatively or quantitatively. In order to make the underlying assumptions transparent and to justify these assumptions it would be beneficial if the system context were explicitly explored.

This is not to say that the context of a system is not considered in IE. Allenby (2004), for instance, recommends that focus in cleaner production should not only be on technology, but the point of this technology in the context of delivering the service, i.e. the role the product plays in society and what this means for alternative products or services to deliver the required function. However, Allenby's paper is conceptual and does not discuss implications for analysis specifically. Explicit consideration of some aspects of the system environment otherwise involves discussion of context on a case study basis (i.e. the influences acting on a specific system are identified), or more generally deals with the needs and drivers of specific industries. Only a small fraction of publications suggests generic, structured approaches to considering system environment and problem context.

A review of case studies shows that environmental influences of particular industries or certain location, such as social influence or governmental agenda, provide both a motivation for performing the analysis and what features of the system are focused on. In the case of LCA, which has a specific system definition, the system context often provides the motivation for the study. For instance, in a LCA study of the Polish energy industry, regulatory pressures, specifically a desire to increase the renewables fraction in national energy provision, as well as the consideration of Poland's future accession to the European Union are cited as motivation for the analysis (Goralczyk, 2003). This influences the focus of the study, which is on renewable energy options. In another example, the system context has implications on model assumptions: In a MFA (coupled with LCA) to assess the impact of the removal of lead from solders on the coupled flows of the metals such as gold and copper, Reuter and Verhoef (2004) cite existing metal process network and waste management infrastructure as providing substantial scope for (product) design, but also limiting change because of the strong path dependency of industry and infrastructure development. On the basis of this, the authors have decided on using dynamic models to capture industry evolution over a longer time frame.

Context is considered in a similar manner when specific industries become the focus of attention. Cohen et al. (2004), for instance, argue that minerals and metals' projects are both consumers and, in some cases (potential) generators of large amounts of energy. Therefore focus on the mineral industry is expanded to consider its interaction with the energy industry. Furthermore, the authors argue that there is a need to look at energy provision and energy services in an integrated manner with key drivers for economic development - both locally and regionally. The authors use LCA to articulate environmental impacts of industry projects, whereas the motivation for using MCDA is that sustainable development problems in the minerals industry are complex. The same argument is made by Basson (2004) who used LCA models in an MCDA framework to support environmental planning in the private sector. The complexity is attributed to the existence of multiple perspectives, incommensurate and/or conflicting objectives, important intangibles and key uncertainties. MCDA was therefore chosen on the basis that it engages with complex problem context.

Some examples are found in the LCA and I/O literature where attempts were made to not only consider, but explicitly capture the system environment. Pehnt (2006) and Reap et al. (2003) specifically recommend the explicitly consideration not only the system environment, but the changes in this environment to improve LCA models. For this, the authors chose different approaches to how this could be done. Pehnt recommended the consideration of different future developments in the background system of LCA to assess renewable energy provision options, whereas Reap and colleagues instead recommend linking industrial models with spatially explicit, dynamic and site-specific ecosystem models. In the paper by Pehnt (2006), a future state of the system was modelled by considering the future characteristics of the background and the model system, meaning that the current and future state were modelled independently of each other. Both approaches are valid, not only for LCA but also for other forms of environmental analysis. However, for industrial network analysis Pehnt's approach has the disadvantage that the separate evaluation of different times means that path dependent developments could not be captured. Reaps's work also has disadvantages. The inclusion of models of the industrial system environment, such as the surrounding ecosystem and the local economy, would constitute a significant increase in data gathering and modelling effort, which may already be significant for the industrial system models. An added issue that may arise from capturing the network environment in terms of models would be the model reliability. While model reliability is always an issue, "environmental" models would have to be based on highly aggregated data and numerous assumptions as they capture systems larger and more complex than the industrial system under consideration. The question remains if under these circumstances going through the added effort of creating environmental model delivers a benefit worth the additional effort.

Another approach that quantitatively captures the network environment is so-called hybrid I/O. This tool integrates sector- and process-level data. I/O is used to supply information for typical products or processes that are well represented by input-output categories, while the rest of the products or processes are modelled by process analysis (Bullard et al., 1978). Because I/O requires less information detail than a process model, hybrid I/O has been recommended as a means to help assess which elements of the technical system environment to include within the system boundary in LCA (Suh et al., 2004). It would therefore be possible to capture the technical environment with I/O to get an idea of material flows in connected systems, while the system in question is described by more detailed process models. While hybrid I/O provides a generic, structured approach to capturing the technical system environment, it does not offer means to engage with social, regulatory or economic influences. It has the further disadvantage that if atypical products are considered, insufficient data may be available to create a reliable I/O inventory of material flows.

Of all the tools in Table 4-1, only MCDA allows the explicit and structured exploration of, mostly intangible, aspects of the network environment and thereby creates a basis for any technical quantitative analysis and interpretation of the outcomes. A further advantage of MCDA is that it can be used in conjunction with any type of system model, not only with LCA models as was the case in the examples cited above. In other words MCDA could be used in conjunction with all of the analysis tools in Table 4-1. MCDA offers the capability to capture and assess intangible issues and encourages the elicitation and discussion of many of the complexities associated with the influences of the network environment and the network itself.

4.2.2 Consideration of Social and Economic Objectives

The tools in Table 4-1 attempt to attain environmental benefit through dematerialisation, substitution, reintegration and/or waste mining and management. However, if changes are to be implemented then it is important to consider the social and economic consequences of a strategy in addition to possible environmental performance improvement. Theoretically all of the analytical tools in Table 4-1 are capable of considering multiple objectives, meaning that social and economic objectives in addition to any environmental issues can be included if the underlying models are appropriately extended. As they are, the analysis tools either quantify material flows, or they quantify the environmental or economic impacts of these flows in a system.

MFA and I/O only assess the quantity, potentially also the routing, of material flows in an industrial system, but do not use indicators to describe the impact of the processing and handling of these materials. These tools are primarily aimed at (identifying means to) achieving dematerialisation. Similarly, MIPS and CERA are limited to material input and energy input into the delivery of a specific product without explicitly referring to the consequences of using these materials or what fuel is used. The magnitude of a flow does not make definitive statements about the quality of the flow and its associated impacts. A small flow may have a huge impact or be composed of toxic material; therefore it would be less desirable than a larger flow of harmless materials. The interpretation if and how bad the use of a specific material is therefore left to the decision-maker. This obscures the consequences of having a certain material or energy flow, or operating a facility or technology. While there is much debate in LCA about the reliability of the inventories, for instance how transferable the generic, aggregated data is (which raises the issue of how to deal with uncertainty in data used in models and therefore the reliability of outcomes) it gives a clearer picture of the particular issues within a product life-cycle. It is less focused on the magnitude of flows, and instead attempts to demonstrate the impact associated with the delivery of a single functional unit.

LCC and CBA convert environmental issues, or “externalities”, into costs. In this case environmental damage may be seen as acceptable as long as it can be paid. Yet assigning a value to environmental or social goods and services in the Pigouvian neoclassical fashion[9] is contentious (Venkatachalam, 2007). Secondly, converting the environmental, social and economic performance of a process, product or system to a final monetary value obscures the strengths and weaknesses with respect to the different objectives. It

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[9] Best known is the Pigouvian tax: A Pigouvian tax is a tax levied on an agent causing an environmental externality (environmental damage) as an incentive to avert or mitigate such damage. (Glossary of Environment Statistics, Studies in Methods, Series F, No. 67, United Nations, New York, 1997)

would be preferable to explicitly identify and measure impacts associated with a given type and quantity of material flow and processing. These tools are therefore not considered further in this discussion.

The consideration of multiple objectives brings additional complications. The different objectives are not directly comparable, there may be no clear order of preference between the objectives and an improvement with regards to one objective may result in the worsening of another. Under these circumstances identifying a single preferred strategy may require some form of ranking and trading-off amongst the objectives. However, MCDA tools exist that are able to address these issues, so called programming or satisficing methods, or multi attribute decision making methods (Belton and Stewart, 2002).

4.2.3 Consideration of Dynamics

While none of the tools in Table 4-1 preclude the consideration of dynamics, time-dependent behaviour of either the system or the system environment is seldom considered in their routine use. Instead a current state or an expected steady state operation of the system is captured – the so-called "snapshot" view. No cases are known where ERA, CERA and MIPS have been applied to dynamic systems. While I/O can contain dynamic elements this is very seldom used (see e.g. Levine (1988)). Yet some authors have pointed out the importance of considering changing system environment when planning systems (Pehnt, 2006) as this influences whether or not a recommended strategy will be valid and effective for future situations as well. The variable behaviour of the system itself, as well as its environment, affects how the system operates and how it evolves, which in turn effects how it should be planned and managed. For instance, Chen and Yu (2001) have shown that recycling affects the ability of a system to respond to changes, making it necessary to increase inventories. This kind of behaviour would not be revealed by steady state analysis.

The dynamics of material flows in industrial systems is considered in MFA models. Examples of this includes fluctuating flows resulting from variable market demand or material availability for instance to model material and energy flows in the timber industry (Muller et al., 2004), the pulp and paper industry (Davidsdottir, 2005). The effect of stocks, i.e. how they accumulate and release material, on future material releases has gotten a lot of attention (Elshkaki et al., 2005; Elshkaki et al., 2004; Kleijn et al., 2000; van der Voet et al., 2002; van Schaik and Reuter, 2004). However, a number of other time dependent developments have hardly been considered, such as the introduction of new technologies or technology learning, whereby a technology becomes cheaper (and more efficient) the more widely applied a technology is. Such developments are harder to predict than changing product demand. Nevertheless, running through different possible scenarios of future events that may occur in the network may give valuable insight into the robustness of recommended strategies, even if the scenarios considered should not come to pass.

Dynamic forms of LCA exist as well, e.g. Stewart and Petrie (1999). However, in these models the system structure remains stable. The problem with dynamic LCA is that it becomes complicated to allocate impacts to a single product if the system structure (e.g. included technologies or facilities, technology performance, materials use, products delivered or material allocation within the system) changes.

A particularly promising approach to dynamic analysis of systems is the combination of LCA and MFA features in some simulation models (McLaren et al., 1999; Reuter and Verhoef, 2004). In these cases the impact of material processing and circulation in a network is determined on a system basis rather than a product basis.

4.2.4 Consideration of Uncertainty

Uncertainty is not widely considered in the analysis tools encompassed by the field of IE, possibly because the tools are used predominately for descriptive/conceptual rather than prescriptive/practical purposes. “Descriptive” in this case implies that the analysis is aimed at providing insights and trends rather than highly accurate quantitative outcomes. However, if decisions are to follow from an analysis, then basing these on flawed data or assumptions can have costly consequences. This may explain why uncertainty has received the most extensive consideration in LCA and life-cycle supported decision making and very little attention in tools such as I/O and MFA.

The uncertainty in LCA is seen as stemming from the information about the physical system (technical uncertainty) or from the subjective choices made when constructing models and interpreting results (valuation uncertainty) (Basson, 2004; Basson and Petrie, 2007b). An example of valuation uncertainty would be a prioritisation between different impact categories. Technical uncertainty constitutes the great majority of uncertainty considered in LCA as valuation judgements are either not explicitly required or acknowledged (Lloyd and Ries, 2007). However, this statement has to be qualified: valuation uncertainty is often neglected in aspirational (learning) LCA studies which constitute the majority of studies, whereas in prospective LCA (supporting decision making) valuation uncertainty receives greater attention.

In the LCA literature sources of technical uncertainty are viewed in terms of how they enter a quantitative analysis, rather than in terms of their origin in the technical system. It is primarily the data quality used for life-cycle inventories that is seen as a source of uncertainty (Heijungs, 1996a; Huijbregts et al., 2001; Kennedy et al., 1996; Weidema and Wesnæs, 1996). Uncertainty in models used and in scenarios were the subject of an older study by the US EPA (US-EPA, 1989), but a more recent review found that such uncertainties were considered in less than half of all sampled studies (Lloyd and Ries, 2007). Uncertainty in models refers to parameters and mathematical relationships. Scenario uncertainty relates to the choices made when constructing scenarios and how locations or situations are captured between different scenarios. Studies that have evaluated these different types of uncertainty varied in their findings: In an LCA analysis comparing two housing insulation options Huijbregts et al. (2003) found that parameter uncertainties dominate when compared to the effect of model and scenario uncertainty. Conversely, for LCA in general Steen (1997) found model and scenario uncertainty to be more important. However, it appears that the relative importance of uncertainty types is dependent on the particulars of the case studies and analysis approach used to determine this importance. Huijbregts et al. (2003), for instance, evaluated only a limited set of scenario choices and model formulations. In a later study assessing the effect of human exposure to pollution, Huijbregts et al. (2005) found that differences in model dimensions, assumptions and equations all resulted in large differences in model outcomes. It appears that no clear statements can be made with regards to which uncertainty generally has a greater influence on analysis outcomes.

The explicit consideration of uncertainty in MCDA has only come about since the early 90's (Anderson et al., 1991; Stewart, 1992). In MCDA, valuation uncertainty is particularly prominent. This is because during the structuring stages, decision-makers, modellers and stakeholders have to make many choices which will to some extent be based on subjective perspectives.

A number of tools have been developed that are able to capture the uncertainties identified here and, if applicable, and propagate these through quantitative models. However, these approaches are not unique to any of the analysis tools MCDA or LCA, or any of the other tools in Table 4-1. Rather, generic uncertainty analysis approaches are used, which are common to many other fields, not just industrial systems research, such as SCM and PSE. For this reason, the available approaches are discussed separately in section 4.4.

4.2.5 Contribution of Analytical Tools to Industrial Network Analysis

The preceding section highlighted the drawbacks of the analytical tools used in IE with regards to their ability to consider system context, multiple criteria, dynamics and uncertainty. The aspects that are deemed desirable and will be incorporated into the industrial network analysis developed in this thesis include

- For capturing the network context: the consideration of the complexity of the network environment and problem context through MCDA.

- For quantitative analysis of industrial networks:
    - LCA's ability of capturing multiple impacts associated with materials and energy flows
    - MFA's flexibility with regards to system configuration and dynamics in the system

While I/O appears to be almost as popular as LCA, as indicated in Table 4-1, I/O is not suitable for industrial network analysis. This is because of the high level of aggregation in industry or commodity classifications, which is cited as its major disadvantage (Bullard and Sebald, 1988; Sakai et al., 2000). Since even the most disaggregated input-output table combines products and production technologies that are heterogeneous in terms of input materials and environmental intervention generation, I/O is not able to capture the process detail, and therefore it is also not able to capture the network characteristics cited in Chapter 3.

4.2.5.1 MCDA for considering the problem context

The aim of MCDA is to ensure quality in the chosen course of action by ensuring the quality of the process that led to the outcome is high and the process is transparent (Belton and Stewart, 2002; Keeney and Raiffa, 1976; Von Winterfeld and Edwards, 1986). More generally, MCDA provides a means of engaging and deliberately exploring tangible as well as intangible issues (Pidd, 1988). For this purpose, MCDA has been used to capture complexity in the energy (Loken, 2007; Zhou et al., 2006), water (Kain et al., 2007) and resource management industry (Mendoza and Martins, 2006). In general, MCDA is designed to help decision-makers, i.e. people confronted with a problem that needs to be resolved, convert initial "messes", i.e. the initial ambiguity, incompleteness, and lack of structure, into clearly defined problems for which suitable outcomes can be developed. MCDA is a flexible approach, applicable to problems varying in the temporal and geographical scope of a system and the number of stakeholders involved. For industrial network analysis, this ability to consider intangible issues is attractive as it will make the influences of the network environment transparent as they will have to be explicitly enunciated. On the basis of this explicit discussion assumptions can be made with regards to the issues included in the quantitative analysis and how these are represented.

MCDA constitutes two to three parts (Figure 4-1): 1) initial problem structuring, 2) problem analysis often through the use of quantitative models. This can be extended to include 3) the implementation of the preferred outcomes. The problem structuring is of particular interest here as it allows decision-makers and stakeholders to explore the complexities surrounding a problem. Problem structuring is important as the results from an analysis will be more defensible if there is clarity and agreement among those concerned on what exactly is the nature, scope and context of the problem. To put this in simple terms, the clearer the question the better the answer (Rosenhead and Mingers, 2001).

In the case of industrial network analysis, the structuring could facilitate with the identification of the sustainable development issues facing an industrial network, the complexity of industrial network itself and the influence of the network environment. During structuring it would for instance be possible to consider the socio-political and economic context of the network which has repercussions for network analysis. For instance, in a poor country an expensive new technology may require additional consideration of how these technologies can be paid for and maintained if there were a lack of qualified local people for the job. If it is decided that these issues may somehow be addressed, the technology could be included in a quantitative analysis of the network development and performance.

A further benefit with regards to the application of MCDA as part of industrial network analysis is that MCDA also recognises that when dealing with complex situations, it is often not possible, sufficient or desirable to limit considerations to any one single objective. MCDA therefore provides means of simultaneously considering a range of economic, environmental and social issues and to examine the performance of a network based on those criteria.

The problem structuring section generally consists of the following four steps, though slight variations in the order of the steps and the detail, i.e. the number of steps suggested, are possible (see Figure 4-1 (Basson, 2004)):

1. The problem definition in which stakeholders are identified and a consensus is reached as to what exactly the problem is. In the case of industrial network analysis the problem involves the identification of the sustainable development issues.
2. The identification of objectives and preferences of stakeholders, in other words in what areas performance of the industrial network should be improved.
3. The identification of performance measures to allow measurement of the degree to which objectives are satisfied.
4. The identification of alternatives, which would constitute the identification of strategies in the case of industrial networks.

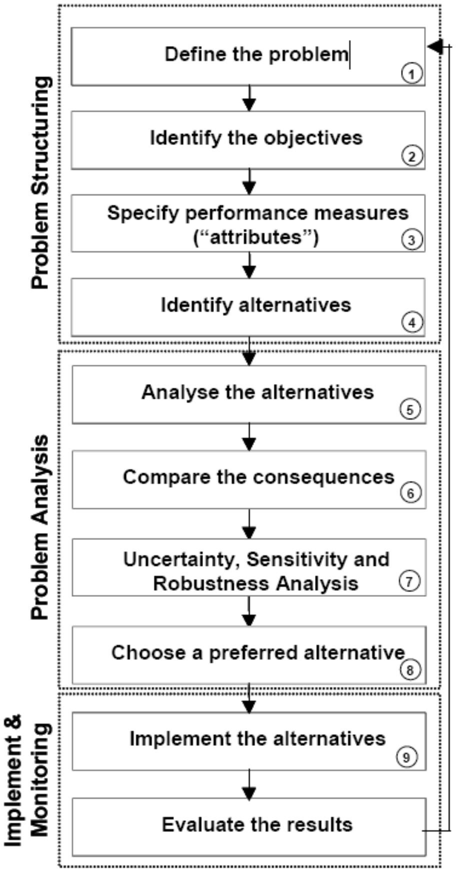

Figure 4-1 Outline of a generic decision process (Basson, 2004)

The approach does not give definite answers on how to tackle a problem, as the simultaneous consideration of multiple, potentially conflicting objectives often means that improvement with respect to one objective will result in deteriorating performance in another area. Rather decision-makers are encouraged to engage with the problem and to reach a decision based on full knowledge of the underlying trade-offs involved.

The second part to MCDA, the problem analysis, involves representing the problem quantitatively. The chosen problem boundary, possible sustainable development strategies can be explored in detail.

While quantitative models such as those used in MFA are flexible with regards to the system they can capture and can accommodate dynamics, and those used in LCA consider the impact of flows in addition to the material flows, these tools would have to be adapted in order to accommodate dynamics, uncertainty and multiple objectives in changing industrial networks. However, if the application of these tools is to move closer to the possibility of implementing the analysis outcomes, then the analysis has to embrace the idea of more flexible and powerful approaches that are able to take the system context, dynamics, multiple criteria and uncertainty into consideration simultaneously. It is therefore useful to look at other system sciences, notably process systems engineering (PSE) and supply chain management (SCM), to see how they capture these aspects. Due to their greater maturity and focus on practical application[10] of analysis results it is expected that modelling approaches have been developed, or are used in these fields are able to satisfy the above mentioned criteria.

4.3 CONTRIBUTION FROM OTHER INDUSTRIAL SYSTEM SCIENCES

Process systems engineering (PSE) and supply chain management (SCM) are both mature research fields that deal with the design, planning and operation of different forms of industrial systems. In this section PSE and SCM are briefly introduced, followed by a discussion of how their approaches to dealing with dynamic problems that potentially have to be considered under multiple objectives can contribute to generating more sophisticated models in IE, and specifically, to industrial network analysis. How these fields deal with uncertainty is discussed separately in section 4.4.

A brief note on the distinction between design and planning: The word “design” is used to refer to the process of generating or adapting a system structure to achieve a certain objective. “Planning” implies that an action is influenced by a consideration of current or future conditions. This action may be the design of a system, but it may also only refer to operations. Conversely the term design sometimes implicitly implies that future conditions have been considered. In the context of industrial network analysis which

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[10] This is for instance demonstrated by the fact that PSE and SCM consider operational aspects as system stability under disturbances and the effect of variations in demand on the system.

deals with the strategic planning (encompassing structural changes), both design and planning will be relevant, if the design considers future developments, and if the planning also considers structural choices.

4.3.1 Process Systems Engineering

Process systems engineering (PSE) is concerned with the design, modelling, operation, management and control of chemical process systems, ranging from the micro-scale (molecules) to the industrial scale (supply chains) (Grossmann and Westerberg, 2000). PSE's origins and development are closely tied in with the advances in computing, which supports the solution of the complex problems that can be formulated around process systems (Edgar et al., 1999). The aim of PSE is the discovery of chemical products, and their design, manufacture and distribution (Grossmann and Westerberg, 2000).

Process systems, i.e. chemical plants, are composed of unit processes, which are connected by material flows, control loops and utility streams that can as a whole to deliver a product to the desired specifications from a given raw material. The choice of system configuration, i.e. the choice of unit operations, the conditions they are operated under, equipment sizing, and the way equipment is linked, has a significant influence on the performance, cost, resilience, operability and environmental impact of the system. Central to PSE is therefore the design of these systems. The design aims to determine a system structure that is best able to meet the requirements, i.e. the delivery of a certain product with a specified quality, within the process and environmental constraints and the possible variations and perturbations. The reason that design is so important for a process plant is that once the structures are in place, the system will have to operate in a comparatively limited operating rage, else its will potentially operate at a loss or sacrifice efficiency. Also, the system is designed for a specific objective, commonly an economic one such as highest net present value (NPV). If environmental objectives would be added after completion of the process system, the opportunities to improve performance in this regard are likely to be more limited than if this objective was considered from the outset.

4.3.1.1 Optimisation for system design

PSE makes use of the following tools to explore and design process systems (Grossmann and Westerberg, 2000; Sargent, 2005):

- Simulation
    - Sequential modular simulation (has been largely replaced by)
    - Equation-based process simulation
    - Artificial Intelligence (AI)/Expert systems

    - Object oriented programming (though this is criticised for driving generalisation of flow-sheets too far and representing its constituents as black boxes and is therefore not always convenient (Sargent, 2005))
- Optimisation
    - Linear programming
    - Parametric programming
    - Stochastic programming
    - Large-scale non-linear programming (NLP)
    - Optimisation of differential algebraic equations (DAE)
    - Mixed-integer non-linear programming (MINLP)
    - Global optimisation

Process design relies heavily on optimisation. This involves the optimisation of process flowsheet configuration, which is analogous to network structure, and operations within this configuration. There are two approaches to solving such problems. 1) They can be solved sequentially or simultaneously. An example of the former is the sequential hierarchical decomposition approach by (Douglas, 1988), where parts of the flowsheet are fixed while others are changed based on heuristic rules. This approach, while simple to implement, often yields sub-optimal configurations. 2) Alternatively, optimisation through mathematical programming can be used (Grossmann, 1996). Here a superstructure is postulated that includes equipment that can be used in the final flowsheet, and the associated interconnections. Commonly these superstructures give rise to nonlinear or mixed integer linear and nonlinear programming models (NLP, MILP and MINLP). Models of the equipment, the connections, and constraints are then posed as part of an optimisation problem, where the objective is typically economical in nature, such as cost minimisation or profit maximisation.

Most process synthesis work has been done on specific types of problems, such as models of heat exchanger networks (Furman and Sahinidis, 2001; Mizutani et al., 2003; Yee and Grossmann, 1990), distillation sequences (Aggrawal and Floudas, 1990; Caballero and Grossmann, 2004), separation synthesis (Floquet et al., 1994), and reactor networks (Kokossis and Floudas, 1991). Superstructures for distillation sequences with heat integration have also been developed (Floudas and Paules, 1988). That PSE analysis tools can be applied to larger scale industrial systems like supply chains, or industrial networks, is demonstrated by the fact that PSE has started to enter the modelling of larger infrastructures and supply chains (Grossmann and Westerberg, 2000; Herder et al., 2000; Shah, 2005) and is in fact seen as a future area of research for PSE (Grossmann, 2004).

While most design problems in PSE begin with a steady state assumption, over the last two decades interest in tackling dynamic problems has increased. These problems deal with transient stages, such as start-up, with batch processes, or with perturbation to parts of the system. Being able to perform dynamic analysis on process systems is necessary for assessing the effect that changes have on the system, especially due to the level of integration and likelihood of negative effects spreading. These problems can be solved with dynamic programming approaches (Biegler et al., 2002; Papamichail and Adjiman, 2004) or with linear and nonlinear programming (LP and NLP) strategies. Dynamic programming in this case does not necessarily refer to time-dependent models. Dynamic programming is a solution approach whereby a problem is solved "backwards", based on the assumption that if the last step of the problem is optimal, it will be part of the overall optimal solution. Dynamic programming thus describes a solution process, and has to be distinguished from dynamic optimisation, which describes the optimisation of a problem over a given time horizon.

Static and dynamic optimisation can easily be combined with so-called multi-objective optimisation (MOO). MOO allows the simultaneous consideration of multiple objectives. However, in this case to trade-off will be required between the objectives as the improvement with regards to one objective often results in the deterioration of at leats one other objective. This phenomenon is know as Pareto optimality. In PSE, MOO has been applied to simultaneously consider between economic and environmental considerations, where the latter are usually LCA based (Alexander et al., 2000; Stefanis et al., 1996; Stefanis et al., 1997). In another example, Hoffman et al. (2001) used MIPS in conjunction with total annualized profit per service unit (TAPPS) to evaluate optimal combinations of process units. MOO has also be used to optimise operational objectives, such as maximizing the styrene flow rate and selectivity and minimizing the total heat duty required by the manufacturing process (Tarafder et al., 2005).

4.3.2 Supply Chain Management

Supply chains are a *"network of firms interacting to deliver a product or service to the end customer, linking flows from raw material supply to final delivery"* (Ellram, 1991). The purpose of SCM is to support operational and strategic planning and decision-making to ensure customer demand is met as efficiently, and as economically, as possible (Beamon, 1998). This involves coordinating the supply of raw material(s) with the often variable demand for the product. This planning includes the coordination of material, cash and information flows among suppliers, manufacturers, distributors, warehouses and retailers. The aspects of supply chains that SCM analyses include:

- global supply chains, where flows become more difficult to coordinate (Vidal and Goetschalckx, 1997),
- inter/intra company supply chains,
- decentralised decision-making,
- uncertainty and stochastics,

- allocation, inventory and scheduling
- supplier-customer coordination, such as information exchange and order management to achieve demand satisfaction.
- supply chain design.

Due to the strategic focus of the proposed industrial networks analysis the idea of supply chain design, which also often falls under the description “strategic planning”, as well as how uncertainty is managed in SCM, is of particular interest. The strategic design of a supply chain requires managers to determine (Vidal and Goetschalckx, 1997):

- the number, location, capacity, and type of manufacturing plants and warehouses to use,
- the set of suppliers to select,
- the transportation channels to use,
- the amount of raw materials and products to produce and ship among suppliers, plants, warehouses, and customers, and
- the amount of raw materials, intermediate products, and finished goods to hold at various locations in inventory.

SCM draws on a series of sophisticated quantitative modelling approaches to support decision-making in industry, such as simulation (of which there are several types, e.g. agent-based modelling, system dynamics, discrete event simulation to name a few) and optimisation, statistics and stochastic, queuing theory (used for operational production planning), game theory (informing the behaviour of agents), and graph theory[11]. These tools are not mutually exclusive and can be used in conjunction with each other. However, only simulation and optimisation will be discussed here in further detail. This will include a consideration of statistics and stochastics, as these are relevant for capturing uncertainty. Graph theory has become redundant since computers became more powerful (Sargent, 2005), whereas queuing theory is not considered further due to its operational focus.

4.3.2.1 Optimisation for system design and planning

The difference between supply chain design and process design is that in supply chains most if not all of the units constituting the system already exist whereas in PSE the system may be designed from “scratch”. In SCM research, system design through optimisation has commonly been used to decide on the location, technology and capacity of new facilities (Beamon, 1998), or for partner selection (Gaonkar and

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[11] Classical graph theory defines networks as consisting of two basic elements: vertices and the edges connecting them. The edges can be directed and weighted, meaning they have an associated direction and magnitude. This value associated with a flow in an industrial network could for instance be a transport distance, an amount transferred, or an environmental impact (Swamy and Thuasiraman, 1981). By this definition, graph theory is already an integrated part of industrial network analysis, as the network structure has been characterised as a graph.

Viswanadham, 2003), rather than designing the entire chain from nothing. Other design examples include investment decisions between alternative products and development projects, to compare the impact of different development and recycling strategies on the supply chain system (Fandel and Stammen, 2004). Nevertheless, optimisation within PSE and SCM problems tends to use the same approaches, as the choice of facility partnership and material allocation are similar to exploring the best option in a process design flowsheet of possible options.

Time dependent elements are also captured. For instance, Fandel and Stammen (2004) used a two-step time structure covering macro and micro periods, representing strategic time frames and operational processes within this strategic time frame. This approach is well known from general lot-sizing and scheduling optimisation models.

Multiple objectives have been considered in optimisation problems in SCM as well through the use of MOO. For the purpose of designing supply chains that contribute towards sustainable development, Zhou et al. (2000) considered multiple conflicting objectives covering social, economic, resources and environmental sustainability in supply chains that cover raw material procurement to distribution. Hugo and Pistikopoulos (2005) considered net present value and Eco-Indicator 99 (Pre´ Consultants, 2000) to choose preferred technologies, capacities and locations in generic environmentally conscious long range supply chain models.

4.3.2.2 Application of simulation for system exploration

Simulation is arguably the more popular tool to use in SCM, based on literature, due to its versatility and the ability to handle much greater detail than optimisation. Simulation possibly also plays a more prominent role in SCM than in the PSE literature discrete events are more common in SCM, which inform the underlying uncertainty – and hence simulation is more attractive. In process systems analysis, the flows within the system can be relatively well controlled. Supply chains, on the other hand, are very much affected by variations in product demand and in the flow of information communicating this changing demand amongst the supply chain members. For these reasons simulation is often used for operational management support, such as planning and scheduling issues of production processes and machine use. These are data intensive problems and models have to be quick to update.

However, simulation is not only popular for decision support surrounding operational problems. It has also been used for strategy development. This is often in the form of "what-if" analysis, where simulation models of the supply chain are rerun for different parameters or even scenarios to determine supply chain response and performance. Terzi and Cavalieri (2004) reviewed 80 papers in SCM that used simulation. Strategic SCM issues that were addressed concerned network design, as well as the development of strategies for exploring collaborative planning, forecasting or outsourcing to third-parties. Simulation has been applied to evaluate alternative supply chain designs; for instance Persson and Olhager (2002), who simulate three alternative designs for a SC in the mobile communications industry in Sweden centred on Ericsson. These authors use five performance metrics: costs, inventory, quality, lead-time and lead-time variability. Hung et al. (2004) developed a generic simulation model to enable informed comparison between different supply chain policies. However, Appleqvist (2004) found in a review of modelling approaches used in SCM literature that simulation appears to be more commonly used for evaluations dealing with continuous improvement, whereas optimisation is more popular for design, or re-engineering of supply chains as Appleqvist calls it, where the supply chain is changed without changing the product.

Kleijnen and Smits (2003) identified five types of simulation: spreadsheet simulation, discrete event simulation, system dynamics, and business games, which involve role play rather than mathematical modelling. This could be extended by object-oriented (used, for instance, by Chatfield et al. (In Press), Glykas and Valiris (1999) and Hung et al. (2004)) and agent-based modelling (also called ABM, used by (Garcia-Flores et al., 2000; Julka et al., 2002; Labarthe et al., 2003)). System dynamics, business games and ABM are commonly used to capture the effect of agent behaviour. However, as the focus of this thesis is on identifying preferred network development and not simulation of actual or likely network behaviour, these tools will not be discussed here in further detail. Spreadsheet simulation is simple and straightforward, but it tends to be too simplistic to capture some of the more complex system features, such as uncertainties (Kleijnen and Smits, 2003). Discrete event simulation is able to capture systems of great complexity, as well as uncertainties. As the name implies, rather than computing the state of a system at fixed time intervals, it breaks processes down into individual events, such as “order received” and “product shipped”. The events mark the beginning or end of an activity, and a set of activities forms part of a process (Ball, 1996). This makes the models mathematically more efficient as it reduces the number of intervals at which the system state is evaluated.

Riddalls et al. (2000) suggest different approaches to capturing dynamics in supply chains: continuous time differential equation models, discrete time difference equation models, discrete event simulation models and operational research techniques. However, like Kleijnen and Smits, Riddalls as well as Robinson (2005) find discrete event simulation to be the most popular tool, likely due to the flexibility with regards to both system and system feature this modelling approach can accommodate.

4.3.2.3 Combination of the two approaches: Multilevel modelling

With the growth of computing power, modelling approaches such as multilevel, or multistage, models have seen a rise in popularity, not only in SCM, but also in PSE. These are able to better capture the complexity and a greater level of detail in both process systems and supply chains. Multilevel modelling can refer to all types of modelling where a problem is solved by the integration, or nesting, of separate models, which thereby allows a greater level of detail to be handled, and can also cater for a combination of different modelling approaches and their respective strengths and characteristics (Ingram et al., 2004). In PSE, multilevel modelling has been applied to the optimal synthesis of process flowsheets (Kravanja and Grossmann, 1997) and heterogeneous catalytic reagents (Lakatos, 2001). In SCM, multilevel modelling has been used for the integration of the tactical and strategic levels scheduling of multi-product batch plants (Bassett et al., 1996). In other examples, optimisation models are used to determine important structural and parametric decisions, and simulation is used to evaluate the distributions of performance measures and constraints more accurately. This has been reported by Karabakal et al. (2000) who studied the VW distribution network in the USA and Gnoni, et al. (2003b) who develop a robust planning procedure for a multi-site automotive components facility.

4.3.3 Modelling Approaches for Industrial Network Analysis

One of the major differences between process systems and larger scale systems such as supply chains and various systems studied in IE, such as eco-industrial parks or industrial networks, is that process systems are custom designed from the outset to fulfil an overarching objective. Industrial networks, which would form through the joint implementation of business imperatives (and ideally through sustainable development strategies), and be created from mostly existing units which were not originally designed for the purpose of integration into an industrial ecology. Though of course, the design of systems is also attractive for new industrial networks that are likely to emerge in the future (Shah, 2005). There exists a relatively short window of opportunity to explore the optimal configuration of such networks before they develop organically - this may be of vital importance in informing national and international policy as well as strategic decisions in industry. Examples of such potential future networks include (Shah, 2005):

- hydrogen, and more generally, networks to support fuel cells;
- water;
- energy - the provision of the energy needs for a country can be viewed as a network which is subject to significant decarbonisation pressures;
- life science products;
- crops for non-food use and bio-refineries;
- gas-to-value (i.e. generating high value products (e.g. very low sulphur diesel) from natural gas in situ);
- waste-to-value and reverse production systems (closed loop supply chains, see e.g. Realff et al., (2000a)).

Yet existing industrial networks could also benefit from design approaches: System design should compensate for the fact that, once established, industrial systems have a limited ability to quickly react to disturbances or adapt to changes. If a network could therefore be designed with such events in mind, in addition to an overarching objective of good environmental, social an economic performance, then the resulting industrial network could be more efficient and more highly integrated (while maintaining a degree of resilience) than one that is left to evolve organically.

For the purpose of design and strategy testing, PSE and SCM use both optimisation and simulation. Both of these tools are capable to monitoring performance of a system with respect to multiple objectives under dynamic conditions. The question remains which tool would be preferred under which circumstances?

4.3.3.1 Simulation versus Optimisation for Industrial Network Analysis

Simulation and optimisation models, which include optimisation of dynamic problems, are fundamentally different: Optimisation is *prescriptive* whereas simulation is *descriptive*. One determines what actions to pursue in order to obtain the best performance of the network within the given constraints; the other describes the network behaviour for a well defined set of circumstances. In simulations, network behaviour is computed sequentially at different time steps over a specified time horizon, whereas in optimisation the performance over the entire time horizon of the network has to be considered simultaneously. This means that a simulation model will base network performance at any time only on the current state, or at the most will only make limited projections. An optimisation model on the other hand takes conditions over the entire time horizon into account. On the basis of this, the model determines the optimal strategy by accounting for and compensating for future events. Simulation and optimisation are thus suitable to different contexts. This can be illustrated by how the two modelling approaches are used in other networks analysis. PSE predominately relies on optimisation to design process plant configurations, whereas SCM makes use of both simulation as well as optimisation to determine network structure and operation. Beamon (1998) observes that for high-level decisions in SCM, optimisation is commonly used, applied to an aggregated network. Simulation on the other hand is used more to assist with planning and scheduling or understanding of operation, but to some extent also for strategy development (Terzi and Cavalieri, 2004) and supply chain design.

A significant issue is the respective computational effort. Because they are comparatively fast to execute, for many practical real-time supply chain applications, such as queuing problems at manufacturing plants, simulation is still the more popular means of decision support. Simulations can be updated and results obtained quickly enough to make it possible to act on them, whereas optimisations would take at least another order of magnitude longer to run. This is due to something referred to as the "curse of dimensionality" (Figure 4-2). The curse of dimensionality states that a problem composed of q number of variables and p number of equations, or constraints, will have 2^{p+q} possible solutions, and a proportional increase in computational time. Nevertheless, this is becoming less of an issue with increasing computing power and the development of more efficient algorithms.

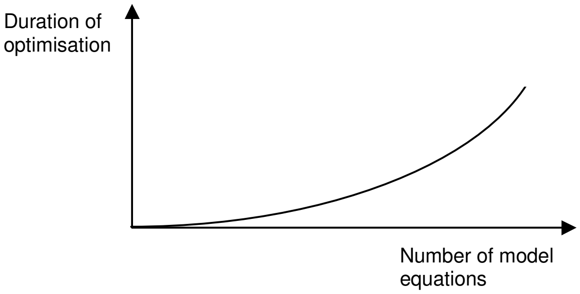

Figure 4-2 Illustration of the "curse of dimensionality": As the size of the model increases, the computational effort increases exponentially

Optimisation appears to be the preferred approach to use when a network structure has to be decided upon. Optimisation, and in particular MOO, can be used to determine the best allocation of resources and explore the improvement in system performance through the introduction of new facilities or technologies with respect to multiple objectives relevant to sustainable development. This is highly relevant to industrial network analysis as those material allocations or technologies could be identified which most strongly contribute to chosen sustainable development objectives. Several authors, such as Diwekar and Small (1998), Seager and Theis (2002) and Van Schaik et al. (2002a), have recommended the use of optimisation to identify preferred means of driving sustainable development. This is largely based on the success of applying optimisation to process design, which is also a form of system optimisation. Yet while modern optimisation routines can help in identifying means to improve performance of industrial systems, with consideration of dynamics, uncertainty, and multiple objectives, optimisation has only been applied in a few cases in IE. Examples include the dynamic optimisation of passenger car recycling (Van Schaik et al., 2002a), and the use of optimisation in conjunction with LCA (Azapagic, 1999; Azapagic and Clift, 1999b, c; Bjork and Rasmuson, 2002). However, apart from Bjork and Rasmuson these approaches do not consider dynamics and none address the effect of uncertainty.

Simulation is less focused on outcome and more on process and behaviour, and is thus better suited to analyse network operation and behaviour. The use of simulation in IE is a little more common than the use of optimisation. For instance, it has been used to explore fuel selection in a dynamic LCA (Yang et al., 2007), in combination with MFA and LCA to analyse metals handling systems (Reuter, 1998) and the replacement of lead solders (Reuter and Verhoef, 2004). Villalba et al. (2007) created a stock-flow model of the fluorine system to identify possible recovery measures. A framework combining MFA and discrete event simulation has been suggested by Wohlgemuth et al. (2006). Other applications of simulation also include agent behaviour focused approaches, such as system dynamics to capture metal ecologies (Verhoef, 2004; Verhoef et al., 2004) and agent-based modelling (Kraines and Wallace, 2006). Casavant and Cote (2004) have suggested the use of chemical process simulation (CPS) software on the basis that these toolboxes capture the detail of the processes, and the complexities involved in the linking of these processes in order to create an industrial ecology. However, using custom designed software on other industrial systems may limit the features of the industrial network that can be captured and analysed.

Multilevel modelling has to date not been applied in any IE analysis. For industrial network analysis, multilevel modelling is of interest as it makes it possible to, for instance, nest models of the processing facilities within a meta-model of the industrial network[12]. Another possible benefit is that multilevel modelling allows the integration of sub-models containing confidential information, where the code subsequently cannot be accessed and manipulated, but input and output could be communicated between models. However, multilevel modelling is very much an emerging area, although one which is expected to expand rapidly. This approach will therefore not be used here, but has the potential to be explored as part of future research.

In this thesis, MOO is chosen as the approach to use in conjunction with MCDA to form the proposed industrial network analysis. The reason for this choice is that industrial network analysis is taking a prescriptive, top-down approach which is concerned with what can be achieved rather than with what will be achieved. Specifically, industrial network analysis should show how, give a certain strategy, a network structure should be established/adapted so that its development achieves *best* possible performance with respect to a set of sustainable development objectives. With simulation, only satisfactory network structures and subsequent development pathways can be identified, “satisfactory” meaning that the performance with respect to the criteria falls within acceptable ranges. Simulation is therefore less suitable in this case and will not be addressed further in this thesis.

4.4 UNCERTAINTY ANALYSIS IN PSE, SCM AND IE

Uncertainties can have a significant adverse effect on the operation and therefore environmental, economic and social performance of industrial systems. It is an issue in production planning and scheduling, choice of location, transportation, finance and process design (Sahinidis, 2004). The problem lies in the limited ability of industrial systems to respond to changes in the system itself or the system environment, in a manner adequate to maintain the desired performance. Uncertainty has received a lot of attention in PSE and SCM, as decisions are implemented in practice and being unprepared for changes, such as a rise in raw material cost or changing material quality, could become costly. The following discussion serves to highlight what uncertainties typically affect design or planning of process systems and

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[12] It would also be possible to combine agent models within a meta-model of the technical system, which could be subject to optimisation.

supply chains. Many of these uncertainties may also affect industrial network analysis. The common approaches these fields use to capture and assess the influence of uncertainty are the discussed and examined for their applicability to industrial network analysis in section 4.4.3.

4.4.1 Uncertainties in PSE

Pistikopoulos (1995) and Ierapetritou et al. (1996) classified uncertainty sources in PSE as

- model-inherent uncertainty (includes kinetic constants, physical properties, transfer coefficients),
- process-inherent uncertainty (flow rate and temperature variations, stream quality fluctuations),
- external uncertainty (including feed stream availability, product demands, prices and environmental conditions, forecasting techniques based on historical data, customers orders and market indicators are usually used to obtain approximate ranges of uncertainty realizations) and
- discrete uncertainty, which refers to the availability of equipment.

An alternative means of viewing these uncertainties is how they are subsequently expressed in the models used during process design and evaluation. At this stage the input, process, output, and to some extent the decision uncertainties become model identification and parameter uncertainty (Kulkarni et al., 2006).

A process plant, for instance, is optimally designed for a specific capacity and operating conditions. While processes are commonly designed with factors of safety, or design factors, to ensure the process can handle higher than expected flows/pressures etc. (Sinnott, 2001b), operation under conditions for which the plant was not designed, such as low capacity, could still lead to sub-optimal performance and financial losses. Opportunities to adapt operation in response to deviations from the expected are limited once the plant is fully operational. The effects of uncertainty and variability therefore have to be considered as far as possible during the design of industrial systems.

4.4.2 Uncertainties in SCM

Supply chains are larger structures than process systems, but also more flexible in that the links between the facilities can change. Unlike process plants, which have a limited lifetime, supply chains can evolve and thereby adapt to a changing environment and survive over the long-term. Uncertainty poses a problem for supply chains due to their low responsiveness. In the pharmaceutical industry, for example, converting raw material into products can range from as much as 1,000 to 8,000 hours (Shah, 2004). Under these conditions, quick adjustments are not possible. It is therefore important that uncertainties, as far as they can be identified, have to be taken into account during the strategic planning stages, where more opportunity exists to include some form of compensatory measures.

Of all the uncertainties involved in SCM, demand uncertainty has perhaps the most significant impact on operational and strategic decisions, as it is the demand for the final product which determines not only the operation of a supply chain, but also the structure. For instance, a growing demand in a certain area will require increased supply. How is this to be satisfied? Is import of materials or products from other areas viable? Or should more facilities open in the area and if so, where are they best positioned and what processes should it use? Clearly many choices about supply chain structure are influenced by the nature and magnitude of product demand.

4.4.3 Uncertainty Analysis Approaches and Potential for Industrial Network Analysis

While uncertainty is also considered in the analysis tools used by IE, especially in LCA, optimisation has not been extensively used with any environmental assessment tool in IE. Therefore very little literature is available to draw on for the identification of suitable approaches. The treatment of uncertainty in conjunction with optimisation has, however, been extensively covered in PSE and SCM and they use common approaches in many cases which are also transferable to industrial network analysis. However, uncertainty analysis approaches which are more commonly used in simulation models are also considered here if these are also applicable to optimisation models.

Uncertainty in PSE and SCM is often quoted in terms of how they affect system design or planning. However, in this thesis a more general characterisation will be adopted to critique the uncertainty analysis approaches with respect to their usefulness in industrial network analysis. This classification and the reason for using it will be discussed in greater detail in Chapter 6, and only a brief description given here. Bonano (1995) distinguished between technical and valuation uncertainty, where technical uncertainties stem from the system and valuation uncertainties refer to subjective judgment influencing choice of how to measure performance. Both technical and valuation uncertainty can be further sub-classified as concerning model form (e.g. system boundary, form of equations), model parameter (e.g. time frame, discount factor) and empirical parameter uncertainties (measurable numbers) (Morgan and Henrion, 1990).

The most common approaches cited in literature deal with the quantitative analysis of uncertainties, dealing with (mainly empirical) model parameters uncertainties. These include interval analysis, fuzzy and statistical approaches (Blackhurst et al., 2004; Klir, 1994a). Another popular approach is scenario modelling, which is amenable to explore different model forms, for instance, to explore the validity of assumptions or different visions of the future (Lloyd and Ries, 2007).

4.4.3.1 Interval Analysis

Interval analysis is popular due to its relative simplicity. Here uncertainty is captured as a range of possible values a parameter may adopt. However its disadvantage is that it may omit potentially important detail about system response if only a few increments are considered, such as the only extreme high and low values. Nevertheless Chevalier and le Teno (1996), who studied the effect of ill-defined data on LCA of building products, contest that often not enough information is available to construct either probability distributions or fuzzy sets. With interval analysis multiple models would be generated, each for a different combination of possible parameter realisations (Frey et al., 1994). Nevertheless, interval analysis has its place as a means of determining if a parameter's uncertainty has a significant impact on a system, especially if information is scarce and a probability distribution is difficult to determine. In fact, interval analysis is ideally suited to assess the effect of model parameter variations in industrial network analysis due to the fact that interval analysis merely interrogates the effect on outcomes of parameter variations without making statements about the likelihood of the particular parameter realisation. This will be justified in more detail in Chapter 6.

4.4.3.2 Statistical Methods

Statistical methods, or probabilistic methods, capture a lack of knowledge or randomness of an occurrence through the use of probability distributions. Probabilities, some would argue, are the best, if not the only sensible means of handling uncertainty (Lindley, 1982). There are two views on probability, the classical, or frequentist view and the personalist, or Bayesian, view. The frequentist view derives the probability of a particular event occurring based on the frequency at which it occurred in a series of similar trials. Morgan and Henrion (1990) point out that the problem with this view is that probability distributions derived in this manner can theoretically only be reliably transferred and applied to another network if the network, or sample population, giving rise to the original data and the network this data is being applied to behave similarly. The Bayesian view offers a means to overcome this problem (Morgan and Henrion, 1990) and it has been used in LCA (Lo et al., 2005) and in SCM (Munoz, 2003). The probability distribution in this case is based on a person's subjective belief that an event will occur, based on the person's current state of knowledge. Probability is thus not only dependent on the event, but also the state of information. This does not mean that the Bayesian probabilities are completely arbitrary, but the subjective element allows adjusting of probabilities to account for different contexts[13].

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[13] Logically, if a sufficient number of trials are observed by a person, then eventually "their" probability should converge with the frequentist probability.

The Bayesian view makes it possible to fit probabilities to uncertainties in empirical data in dynamic industrial network models. Industrial networks will require numerous simplifications and assumptions, especially if the model has a strategic focus and reconciliation of different sources of information. Much of the data may thus not be directly applicable, but will have to be adjusted somewhat to fit the network, as well as the network processes and their representation in the model.

Stochastic optimisation, or stochastic programming, is the most common approach to handling uncertainty in optimisation problems concerning physical and chemical systems, production planning and scheduling systems, location and transportation problems, resource allocation and engineering design (Dantzig, 1955; Guillen et al., 2005; Sahinidis, 2004). It encompasses a variety of methodologies, such as two-stage, multi-stage and infinite-horizon stochastic programming. In stochastic programming the uncertainty is seen as a number of possible states of the world (states where prices or expected demand differs) each with a given probability of occurring. In two-stage stochastic programming, the decision variables are divided into those that have to be decided "here-and-now", such as investment decisions and those that are subsequently decided after the uncertainties have been realised, in the so-called the "wait-and-see" stage (Birge and Louveaux, 1997; Diwekar, 2003). A multi-stage stochastic programming problem is an extension of the two-stage stochastic programming problem. In this case a number of opportunities to make decisions as time goes by are available - a more realistic approach - and subsequent uncertain realisations of the world. The latter are often dependent on the decisions taken. Stochastic optimisation is attractive for industrial network analysis as it allows system structures and development pathways to be identified that is "best" under the current and expected conditions, and for the chosen sustainable development strategy. Two-stage stochastic optimisation is deemed sufficient to demonstrate the approach in this thesis, assuming that investment decisions are only required initially.

Time varying, or time dependent uncertainties, such as price fluctuations can also be accounted for by means of stochastic processes. It is an attractive means of capturing variability of parameters in dynamic process models, for instance to capture time-varying behaviour of parameters in batch processes (Rico-Ramirez et al., 2003; Ulas et al., 2005). It has only been used in one known model falling in the realm of industrial ecology. Diwekar (2005) used a stochastic process to capture variations in human mortality in an model optimising the sustainability, as represented by Fisher information, of a local ecology. Stochastic processes offer a realistic means to represent parameters that have fluctuating values over time and are therefore relevant to industrial network analysis. However, these processes increase the complexity, and hence the computational effort of an optimisation significantly. At the same time they are not expected to provide much additional insights into the validity of the industrial network analysis approach that are not also provided by assuming smooth trajectories for a parameter's development over time. Stochastic processes will consequently not be considered in this thesis, but may be included in future research on the subject to extend the capabilities of the approach.

4.4.3.3 *Fuzzy Approaches*

The seminal paper on fuzzy dynamic programming was written by (Bellamn and Zadeh, 1970), although Zadeh made a start in this field in with the introduction of fuzzy sets (Zadeh, 1965). Fuzziness implies that a goal, consequence and/or constraint of an action be in the vicinity of a nonfuzzy value. Saying someone is tall is a fuzzy statement, where as someone has a 70% of being tall is both probabilistic (70%) and fuzzy (the meaning of “tall”).

Fuzzy programming takes a different approach to stochastic programming. Instead of using probability distributions, in fuzzy programming random parameters are treated as fuzzy numbers and constraints as fuzzy sets, where some violation of the constraints is allowed. A membership function is used to describe how far a constraint is satisfied. The degree of membership ranges between 1 (meaning an element is a member of a set) or 0 (the element is not a member of the set).

Fuzzy programming is seen as a viable, simpler alternative to stochastic programming, but evidence suggests that results obtained through stochastic analysis are of higher quality (Laviolette and Seaman, 1994; Liu and Sahinidis, 1996), but this is not uncontested (Klir, 1994b). Some authors have found the results comparable (Tan et al., 2002). However the statistical approach is by far the more common and therefore better developed. Statistical approaches are therefore also used to consider uncertainty in this thesis.

4.4.3.4 *Scenario Modelling*

Scenario modelling has been used to describe a set of models where everything from parameters or mathematical expressions are varied (Geisler et al., 2004; Huijbregts et al., 2003; Maurice et al., 2000), or to describe how a modeller’s choices impact model outcomes (Lloyd and Ries, 2007), for instance how different allocation methods in LCA affect outcomes (Huijbregts, 1998). Scenario modelling is therefore capable of handling both technical and valuation parameter and model form uncertainties. While the cited literature in this section deals with simulation models, the approach is applicable to optimisation and therefore relevant to industrial network analysis. In fact, scenarios could provide insight into how model form or future development affects the preferred network structure and development identified, and subsequently conclusions can be drawn about the viability of a network design and sustainable development strategy. However, to avoid confusion about what is varied between scenarios, scenario modelling will be referred to under different names in this thesis based on the uncertainty type dealt with. Generally, scenarios are defined as descriptions of fundamentally different possible futures (Hertwich, 2005b; Schoemaker, 1993) and this definition is adopted in this thesis. Scenario modelling will therefore be useful to explore different possible futures. In the case of parameter uncertainties the equivalent of scenario modelling is the same as interval analysis. When different mathematical expressions or model forms are explored, this will be referred to as sensitivity testing.

4.5 CONCLUSIONS

The aim of this chapter was to

- demonstrate that current IE analysis tools have to date not extensively engaged with important industrial system analysis aspects such as 1) influence of the system environment (which together with the analysis objective informs the problem context), 2) dynamics of the system, 3) the consideration of multiple environmental, economic and social objectives, and 4) the influence of uncertainty.
- identify attractive features of the existing analysis tools that could be incorporated into the proposed analysis due to their ability to address the above four issues.
- show that the related industrial system research fields of PSE and SCM use modelling approaches that capture network detail, dynamics, multiple objectives and the influence of uncertainty and are therefore attractive to include in industrial network analysis.

The critique showed that existing environmental assessment approaches are limited, or simplistic, in their view of system and contextual complexity introduced by the system environment and the objective of promoting sustainable development. However, the critique also highlighted that MCDA, LCA and MFA possess attractive features: MCDA with its problem structuring is suited to capturing problem context and is capable of dealing with multiple objectives, LCA considers multiple possible environmental impacts of flows and not just the magnitude of flows and MFA is flexible with regards to the system form it captures and easily handles time-varying behaviour. For these reason it was recommended that the quantitative analysis of industrial network analysis be embedded in a MCDA approach, impacts of material flows should be considered (in light of the sustainable development objective, social and economic in addition to environmental impacts should be considered), and that network structure should be flexible, also over the time frame of an analysis.

Consultation of the literature in PSE and SCM to determine what modelling approaches exist that could meet the criteria of the industrial network analysis. It was found that PSE and SCM invest a lot of research into system design and planning to ensure a proposed system or system changes are viable over the long term and achieve their objectives as best possible. This matches the aim of industrial network analysis, which is intended to be used to determine network structures and development pathways that show best performance with respect to sustainable development objectives for a given environmental strategy. For design and planning, PSE and SCM both use optimisation and simulation. Optimisation, specifically multi-objective optimisation, is chosen for industrial network analysis. Unlike most of the environmental assessment tools, it not only describes the structure and development of a system, but offers opportunity to explore how a system *should* be designed and operated with respect to multiple relevant sustainable development objectives. While simulation is not explored further in this thesis, it may however be attractive to include it in future work, for instance to learn about system behaviour through running multiple scenarios (a benefit of simulation suggested by Rejeski (1998)), or to capture agent behaviour (e.g. through agent-based simulation).

In this chapter it was discussed how PSE and SCM can contribute towards more sophisticated quantitative analysis in IE. However, industrial network analysis may also be of interest to the fields of PSE and SCM, as these have to date not extensively engaged with sustainable development considerations in their analysis. Industrial network analysis could be used in PSE, for instance, to a new process plant, should position itself in a network, or if new technologies have a chance of competing with existing ones. An example of how industrial network analysis could be of interest in SCM was already supplied by Shah (2005), for the planning of networks that may emerge in future (see section 4.3.3).

Only analysis approaches in PSE and SCM potentially relevant to industrial network analysis were discussed in this chapter. It is expected that these fields are able to contribute more broadly to analysis in analysis in IE than was indicated in this chapter, for instance for insights into operational planning or, as already suggested, into simulation approaches for the exploration of agent behaviour.

The industrial network analysis methodology is introduced in Chapter 5, showing how the above identified tools and modelling approaches are integrated to develop the analysis methodology. Chapter 6 will deal exclusively with how uncertainty enters industrial network analysis and how it can be handled by using the uncertainty analysis approaches identified in this chapter, in order to increase the likelihood that chosen networks and strategies are robust.

5

DEVELOPMENT OF INDUSTRIAL NETWORK ANALYSIS FOR SUSTAINABLE DEVELOPMENT

5.1 INTRODUCTION

The aim of the industrial analysis methodology presented in this chapter is to firstly provide a structured approach to considering the network environment and the context this provides together with the sustainable development issues facing industry discussed in Chapter 2. Secondly to provide a flexible, quantitative approach to capture and analyse the richness of the industrial network described by the characteristics presented in Chapter 3. For this purpose, the industrial network analysis developed in this thesis draws on a analysis approaches used in the fields of PSE and SCM, as well as being informed by the guiding framework of industrial ecology and its associated suite of analytical tools. These tools include problem structuring, multi-criteria decision making, as well as quantitative tools, such as scenario analysis, optimisation and various types of uncertainty analysis approaches, although these latter will be discussed separately in the next chapter. While scenario analysis is also used to explore the influence of uncertainty on analysis outcomes, it is discussed here due to its far-reaching effect on the analysis methodology.

In this chapter the framework of the industrial network analysis is described. Based on multi-criteria decision analysis, it uses problem structuring to facilitate with explicitly capturing the problem complexity until a clearly defined problem emerges. The insights from this process are then used to build quantitative models with which to explore the network, learn about it, and hopefully emerge with useful recommendations on a network structure and network development pathways that contribute to sustainable development. The methodology, with the problem structuring and quantitative analysis steps, is outlined in Figure 5-1 This methodology is based on a multi-criteria decision approach, but adapted to the requirements of industrial network analysis.

It should be kept in mind throughout this section that all the stages of the methodology introduce a degree of uncertainty, either due to assumptions, or the underlying values or personal judgements which shape model development. These uncertainties tend to influence the quality of the analysis outcomes. This is pertinent not only during model development, but from the initial problem definition all the way through the structuring and analysis process. It is an explicit aim of this thesis to engage with uncertainty from the very start, identifying its sources within the model of the network and its environment , characterising the types of uncertainty introduced, how they influence outcomes, how they can be accounted for, and, if necessary, reduced or accommodated. Given the significance of uncertainty management within the network analysis, this will be dealt with separately in Chapter 6.

5.2 DESCRIPTION OF PROBLEM STRUCTURING

Initially, any problem will be unstructured, or a “mess”, characterised by the existence of multiple perspectives, incommensurate and/or conflicting objectives, important intangibles and key uncertainties (Rosenhead and Mingers, 2001). This is also true of industrial networks, where not only the potential of multiple diverging perspectives, but also the complexity of the sustainable development target, the industrial network and its environment obscure a clear course of action. Problem structuring aims to break the problem and its resolution down into more tractable steps. These steps are (Figure 5-1, Steps 1-5[14]):

1. The definition of the problem
2. The definition of the geographical and temporal and network boundary
3. The identification and engagement of stakeholders
4. The choice of objectives
5. The choice of indicators which can be used to capture the performance of the network against these objectives

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[14] Step 5 is the quantitative analysis which is addressed in section 5.3.

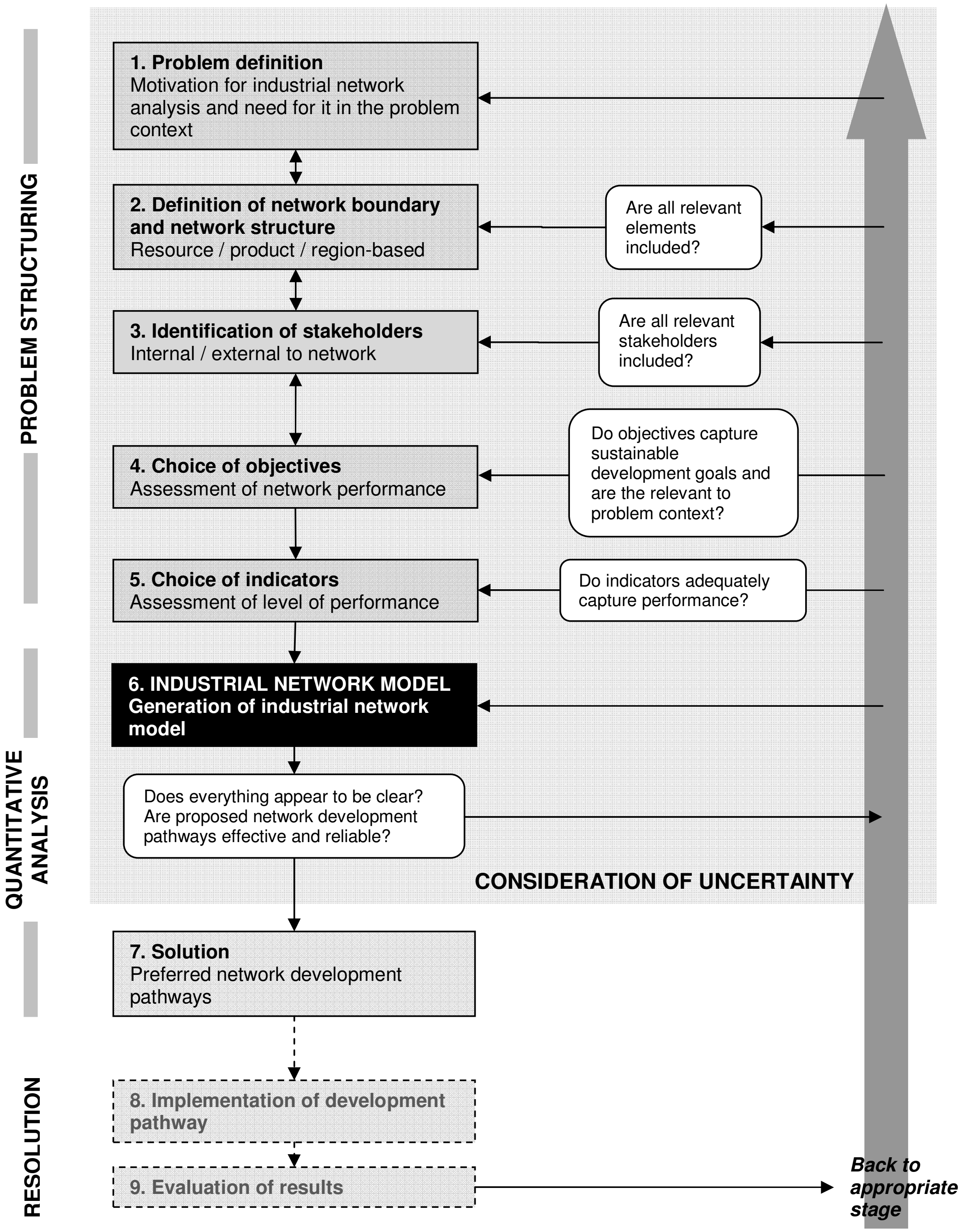

Figure 5-1 Overview of the industrial network analysis methodology. Note that this is an iterative process.

Some aspects of this proceed from a technical awareness: first focusing on the technical aspects, then relating these to the context of the problem, and finally by taking into account the particular situation. For other stages, the process is reversed: information should be first obtained from the decision-maker by relating to the situation of the decision, then seeing it in its context, and finally in its technical aspects (Brugha, 2004).

A systematic approach to problem structuring has the benefit that it forces all considerations to be stated explicitly and in an organised manner, thereby making the process transparent. While it appears to be a sequential process, problem structuring will benefit from being handled iteratively as many insights into the network, its behaviour, its situation and its performance may only reveal themselves in later stages as the problem is analysed in more and more detail. No matter how much effort is invested in including all relevant features and avoiding all oversights and redundancies, in practice this can hardly be achieved right from the start.

To refine the industrial network analysis it may be necessary to revisit preceding stages and either *elaborate* on some aspects that turn out to be important and require representation in greater detail, or *simplify* those aspect that are found to be redundant and irrelevant to the pursuit of improving sustainability (Morgan and Henrion, 1990). After each stage it should therefore be checked if the outcomes are acceptable and can be generally agreed on (indicated in Figure 5-1). If there are problems then the process may have to be repeated or an appropriate previous stage will have to be revisited.

The remainder of this section provides a detailed description of the six problem structuring steps, starting with the definition of the problem.

5.2.1 Problem Definition

The very first step to structuring the problem is defining what exactly the problem is. While this seems straight forward, it often is the case that different parties have different views about what the issues are and the absolute and relative importance of these issues. **The stated goal of analysis in this thesis is to identify and evaluate network structures and network development pathways for promoting sustainable development in industrial networks.** However, what does sustainable development mean in the context of a particular network? What environmental issues can be identified and which are the most important to address? It has to be emphasised that there is no “right” problem that merely has to be uncovered. Rather, the problem is a subjective construct of, in this case the modeller or decision-maker, and therefore there may be numerous ways to represent the problem. The problem definition may therefore only unfold progressively through discussion and explanation of the different perspectives. The problem definition serves three purposes (Rosenhead and Mingers, 2001):

- It serves to tackle disagreements and build consensus amongst the parties involved.

- Through explicitly describing the problem it makes the motivation for a resulting course of action transparent.
- The explicit definition of the problem streamlines all following information structuring steps.

The problem definition therefore ensures better quality solutions from the analysis by making it more likely that it addresses issues that can be generally agreed on as important and worth addressing. The problem definition to a significantly influences the definition of the industrial system included in the network boundary.

5.2.2 Definition of Network Boundary

Choosing appropriate values for both the geographical and temporal scope of the network model, and its resolution is one of the major challenges of this type of “complex systems analysis” as industrial networks are open and have numerous interactions with their environment.

5.2.2.1 Spatial scope and network structure

The spatial network could be delimited by either resource-, product- or location-based considerations, or a combination of these, as defined in section 3.2.3. While this view may be influenced by the sources of environmental issues already identified during the problem definition, it may have to be updated based on the strategies that are chosen. In all cases, the life-cycles of the products circulated should be taken into account as any changes tend to propagate up and down the supply chains which intersect with the industrial network. For instance, the use of recycled materials will require less primary material to be harvested or mined, but it may require additional processing, thereby creating added impacts after use. It is recommended to start the boundary setting with a brainstorming of the possible materials/energy/products, existing created nodes and technologies as well as potential new additions that could be included in the new or in an existing network. For the region-, product- and resource-based network types (as per Chapter 3) this mapping would involve the following steps:

Region-based

- listing existing facilities and flows between them
- listing of available secondary materials and energy in the region, as well as their sources
- listing of existing facilities that could accept the secondary material or energy
- brainstorming of possible technologies that through their addition to the network, would contribute to implementing sustainable development strategies, such as material cycle closure or efficiency improvement.

Product-based

- mapping the current product life-cycle, i.e. all processes from cradle to grave
- listing of alternative raw materials for this product, if possible
- listing possible alternatives for delivering the functionality of the product, for instance re-design or replacement through service, if possible
- listing possible uses for waste products generated along the product life-cycle
- brainstorming of possible technologies that through their addition to the network, would contribute to implementing sustainable development strategies, such as material cycle closure or efficiency improvement.

The resource-based view of the industrial network is similar to the product-based view with the difference that not merely one product is under consideration, but all products that result from this resource. Therefore the network mapping for the “resource-based” view would require the same approach as the “product-based” view, with the addition of listing of all existing products resulting from the resource in question. However, it may not be possible or even effective to consider all product life-cycles originating from a particular resource, or to include all options for material reintegration without the network analysis expanding to an unmanageable size. Through the use of qualitative or simple quantitative analysis and through consultation with stakeholders and experts it should be possible to eliminate a number of the listed technologies, raw materials, material/energy sources, material/energy receivers on the basis of cost or technical feasibility. For instance, a facility may be so far away from a potential supplier that transport impacts make it infeasible to consider this option in detail. Failing that, some other criteria may have to be adopted whereby the scope of the network can be reduced to manageable size. For instance, the resource-based network analysis can be limited to consider only those products that use the majority of the resource. Alternatively focus can be turned to regional use of that resource, or to product chains based on only a particular source of the resource.

In addition to the above technical considerations of the facilities, technologies and materials/energy/products in the network, it is also important to note aspects like

- Technology market penetration
- Market demand
    - Demand pattern (e.g. in the case of energy centralised versus distributed)
    - Type of demand (e.g. for electricity, heat, fuel)
    - Current stocks and flows in these markets

The technology market penetration will influence the availability of a new technology as well as its cost. The market demand in turn influences the current, but also future, behaviour of the network. For instance, should substituted material be acceptable, or would the demand continue to exist for the original resource?

Once the initial brainstorming on network structure is completed, attention can be brought to considerations of the network environment. These include:

- Institutional arrangements
    - taxes and incentives
    - investment schemes
    - partnerships
- Socio-political background
    - government agendas
    - social situation (developing country, developed)
    - industry players (consideration of perspectives and company objectives)
- Condition of natural environment (drought, erosion, flooding, etc)

Once the final facilities and new additions have been decided upon, information needs to be gathered about

- capacities and location of existing facilities, performance specifications of facilities (i.e. environmental, technological, social, economic performance)
- material quantities and properties
- Ability of existing facilities to deal with quantities and properties of waste or by-product materials
- Ability of proposed new technologies to deal with quantities and properties of waste or by-product materials
- Possible capacity and location of proposed new facilities, performance specifications of facilities (i.e. environmental, technological, social, economic performance)
- Existing connections (in the form of shared resources, contracts or linking infrastructure) and strength of those connections, and how robust these are

5.2.2.2 Temporal scope

Industrial network models also exhibit significant dynamics and decisions that seem feasible or attractive at one time and under prevailing conditions may fail to pay off in the face of future developments. The temporal boundary, or the model time frame, thus needs to be set in such a way that the influence of the most long-term or most distant (foreseeable) future developments is captured within the system model.

Apart from the duration of the model, its resolution has to be set. Should the model run at monthly or yearly increments? Is an aggregate representation of the facility's processes sufficient, or should the unit processes be captured as well. The required level of detail of the industrial network models will be primarily guided by the aim of the analysis. As the focus of industrial network analysis is a long-term/strategic one with relatively broad network scope. If good quality data is available that adequately describes aggregate nodal function, then detailed process models should not be necessary. The behaviour or operations of the network entities can be represented in an aggregated fashion for this.

5.2.3 Identification of Stakeholders

Stakeholders will have to be involved to get the different network specific perspectives on what the issues are and to ultimately reach a shared understanding of the situation. Should stakeholders be unavailable or can for some other reason not be included, their perspectives can be attained through role play. The problem definition and the identification of stakeholders are interrelated, as the problem definition identifies who the relevant stakeholders are. At the same time, the stakeholders are the ones whose input helps further define and structure the problem.

Stakeholders relevant to the analysis are considered to be

- parties interested in increasing (sections of) the network's sustainability,
- parties that have control over (sections of) the network and whose cooperation is required in order to create a more resource efficient network (aka agents), and
- other parties affected by the outcomes.

Stakeholder participation for the purpose of promoting sustainable development in networks serves two purposes. Firstly, ideas for improvement can be generated, and an agreement or acceptance reached on the issues underscoring the analysis, as well as potential plans of action. Secondly, many of these stakeholders may participate in any subsequent implementation of the course of action.

Two questions to be answered when selecting the stakeholders to patriciate in the process of structuring the problem and determining preferred network structure and development pathways (Belton and Stewart, 2002) 1) Who are the stakeholders that are of interest, and 2) should all these stakeholders be involved? Involving as many diverse stakeholders as possible may be useful to determine their input, and potentially also their cooperation will be needed to achieve sustainability on a network wide level[15]. Stakeholders may influence indicator selection (as no set of indicators is predefined in industrial network analysis) through the identification of particular issues and concerns. Stakeholder consultation can be in the form of surveys, the formation of focus groups, community panels, corporate advisory panels or through written communication. The perspective of stakeholders not participating in the analysis process can still be included through role play.

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[15] Should individual agents be interested in increasing sustainability within their area of control they do not need to consider the entire network they operate in or consult other agents. However, they may wish to do so if their actions are expected to have significant repercussions on the network.

While there are arguments for involving as many stakeholders as possible, meaningful discourse and implementation becomes difficult if groups become larger than 20 (Shaw et al., 2004). So called large group intervention methods (LGIM) exist that outline the management consultations with large groups of stakeholders (for example, Future Search (Weisbord and Janoff, 1996) and Participative Design (Emery, 2000). They claim to support decision-making, but are mostly useful to companies for the purpose of facilitating communication, innovative thinking, collective learning, option generation and revitalizing community spirit (Leith, 1999). The problem is that many stakeholders will not necessarily be agents in the network under consideration, and this increases the chance of suggestions for interventions in the network being made that are infeasible. These problems tend to be what the operations research (OR) community calls "wicked" problems. These are problems where views of the problem differ, parties involved have differing beliefs and values, the nature of the problem evolves over time, little hard data is available and resources are limited. A significant part of OR is dedicated to problem structuring methods (PSM), which give guidance on how to approach wicked problems in order to attain solutions. Volume 57 of the Journal of the Operational Research Society is dedicated to PSM and presents an excellent source of reference (e.g. Rosenhead (2006) and Shaw (2006)). In industrial network analysis, the number of stakeholders involved may easily reach large numbers. It may therefore be preferable to limit stakeholder involvement to participants in the network, i.e. the agents. The possible perspectives of other parties could be considered through role play.

A number of techniques exist, aimed at facilitating stakeholders in eliciting their preferences and specifically at structuring problems. These can range from simple questionnaires to elicit issues and objectives in a small homogeneous stakeholder group, like one internal to an organisation, to techniques involving the facilitation of discussion and conflict resolution when a large number of diverse stakeholders are involved. The latter is the more likely case when dealing with industrial networks. Problem structuring techniques all make use of models to support the problem definition. Examples are:

- cognitive maps (Eden, 1992; Eden, 2004)
- problem frames (Jackson, 2001; Wallace et al., 2006)
- influence diagrams (Clemen, 1996; Morgan and Henrion, 1990)
- means-ends objective networks (Clemen, 1996; Keeney, 1992)
- conceptual models for learning (Soft networks methodology) (Checkland, 1985; Checkland, 1981; Checkland, 1988)

Shaw (2004) suggests that only the actual decision-makers that are responsible for or able to affect change be included in a problem structuring workshop. These parties must feel a sense of shared problem ownership and group commitment, as this increases the chances of successful implementation (Beckhard and Harris, 1977; Dickson et al., 1996). Rather than being a group consultation exercise, negotiation, consensus and commitment to the course of action must be supported.

5.2.4 Choice of Objectives

The primary objective of the industrial network analysis in this thesis is to promote environmental sustainability through the application of one or more of the strategies outlined in Chapter 2. However, network performance and strategy feasibility will also depend on achieving or maintaining "good" social and economic performance. These overarching objectives will have to be refined into objectives that are specific and relevant to the industrial network in question. Starting with a set of general objectives and refining them to fit the network constitutes a top-down approach to analysis. It is more common than the alternative. The bottom-up approach would begin with the network in question to identify its specific impacts thereby defining objectives. The two approaches are however not mutually exclusive and swapping between them can help create a more comprehensive set of objectives (Stewart, 1992). While the top-down approach is more commonly used and would appear consistent with the top-down planning approach of this analysis, an iterative approach is preferred for industrial network analysis. This way, no predefined set of objectives is applied in each case, but instead the choice of objectives to represent social, economic and environmental performance is based on the particular network. For instance, while the overarching objective is to improve social performance, the bottom-up view of the network may mean that maximising rural development by means of electrification the particular network may be chosen as the relevant objective to address in this case (See Figure 5-2).

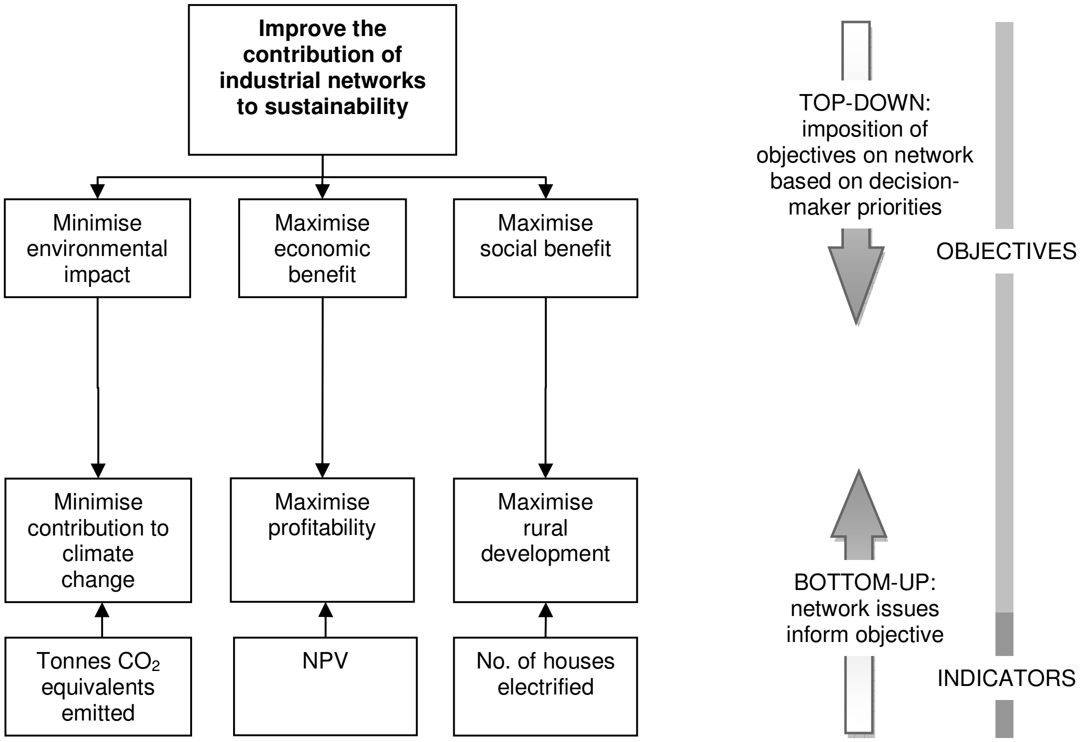

Figure 5-2 Example of an objectives hierarchy that shows the relationship between objectives and criteria, for a specific case study of electricity generation (see Chapter 8)

Figure 5-2 shows an example of an objectives hierarchy that may be used to assess the performance of an industrial network focused on the delivery of electrical power in rural areas (which is the focus of one of the case studies pursued in this thesis – Chapter 8). Objectives hierarchies are useful means to present the key factors according to which a course of action will be chosen.

5.2.5 Choice of Indicators

With the set of objectives having been determined, the next step is to identify indicators to adequately represent the performance of the network with respect to the objectives and to measure the level of network performance.

5.2.5.1 Types of indicators and desired characteristics

In addition to being measurable and quantifiable, a good indicator for decision making support should also have the following characteristics (Belton and Stewart, 2002):

- *Value relevance* – They should adequately represent performance in the objectives.
- *Understandability* – It should be clear what the indicator represents and why it was included.
- *Non-redundancy* – Care should be taken to avoid indicators that represent the same impact in different forms.
- *Judgmental independence* – The change in one objective should not result in a change of the relative importance for the decision-maker.
- *Balancing completeness and conciseness* – How much information is enough?
- *Operationality* – The indicator and the associated numbers should be manageable.
- *Simplicity versus complexity* – The quality of the analysis should not be compromised by giving preference to simpler indicators?

5.2.5.2 Existing indicator sets

As with the sustainable development concepts and tools discussed in Chapters 2 and 3, a large number of sustainability indicator sets have been developed. No one indicator set is universally accepted, largely due to the ambiguity of the definition of sustainable development, the assessment purpose (financial reporting, environmental improvement) as well as the difference in the contexts in which the indicator methodologies are applied and the systems they are applied to. The indicator sets differ in underlying methodology, terminology and data collection (Parris and Kates, 2003). Indicator scope can range from a few environmental or economic indicators to more holistic sets that span environmental, social, economic, as well as institutional and political aspects, sometimes using over a hundred individual indicators (e.g. Global Reporting Initiative, ISO 14031).

In order to assess industrial network performance and determine preferred development pathways for a given network, it is necessary to predict network performance under changing conditions. Many reporting indicators are therefore of little use for industrial network analysis. Their scores are measured empirically and adequately reflect a status quo, but for many no models exist that could link their performance to network changes. Incidences of corruption or discrimination, for example, can be accounted for as they get reported to organisations or institutions, but they cannot, at least reliably, be correlated to any feature that would be captured in a technical network model.

The numerous indicator sets can be classified according to the scope of system they are aimed at (Veleva and Ellenbecker, 2001). This ranges from monitoring compliance with environmental guidelines at individual facilities, to assessing the performance of countries and regions, such as the Wellbeing Index, the Global Scenario Group and the Ecological Footprint (Figure 5-3). The most relevant to industrial network analysis, due to the similarity in system scope, are those at the supply chain or life-cycle level, though indicators form other methodology for other levels could be considered as well. It has to be kept in mind though that the use of the same indicator at different levels in the network may result in different outcomes, and therefore suggest different actions. This point will be taken up again in the following discussion.

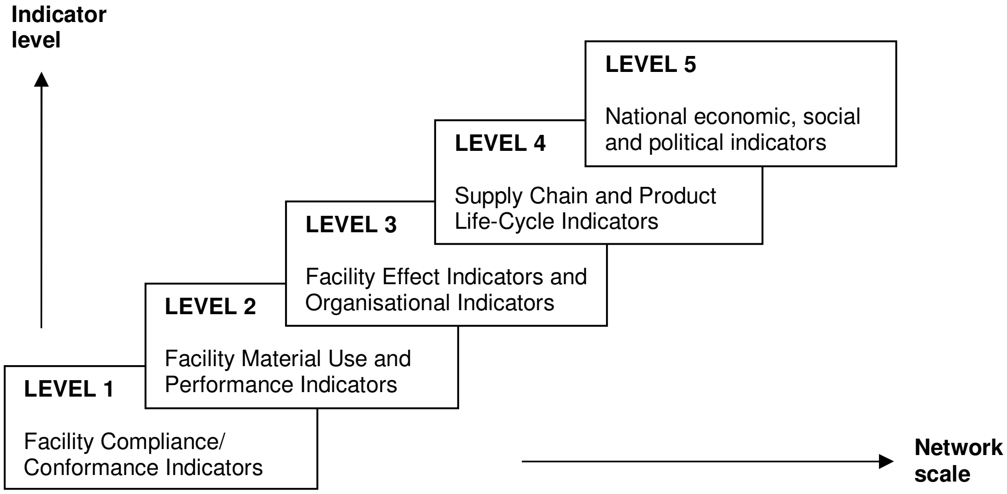

Figure 5-3 Existing indicator methodologies aimed at different system levels (based Veleva and Ellenbrecker (2001))

5.2.5.3 *Indicators for industrial network analysis*

Industrial network indicators should encompass the impacts associated with resource extraction, manufacturing and production, transport, use and the post-consumer fate of products; in other words, the life-cycle of the included materials. In a holistic assessment, environmental indicators should account for the diverse nature of impacts, which can range from toxic emissions to energy and water consumption, and land use. The effects on biodiversity, resources and human health have to be considered. Industrial network indicators therefore have to meet the following requirements:

- They should satisfy the criteria listed in section 5.2.5.1.
- They have to encompass the network as a whole.
- They cover environmental, social and economic performance.
- They consider the sustainability issues as well as the socio-political, environmental and economic situation of the individual network.

The first two points progress naturally from the arguments given in Chapters 2 and 3, whereby industrial network analysis aims to improve performance with respect to sustainable development for the network as a whole. Therefore the network has to be considered in its entirety and the indicators have to provide an indication of the holistic performance of the network.

The third point suggests that new indicators can be developed which are relevant and tailored to the network in question; these may be used either instead of or, in addition to, existing indicator sets. The use of available indicator sets has the advantage that a) results may be comparable to other systems where this indicator set has been applied and b) the indicators are tried and tested. Indicators that are used repeatedly will have been refined to a point where they have the characteristics listed in 5.2.5.1 and are seen to adequately link behaviour to performance. However, as already mentioned, many of these indicator sets are developed for a specific purpose and may therefore not adequately capture the diversity of issues and network characteristics and performance.

The existing indicators described in the previous section can provide a basis from which indicators for industrial network analysis can be chosen or, depending on the network, adapted to better fit the context. The following discussion extends this consideration.

Environmental indicators: From an industrial ecology perspective, the closure of material cycles and the prolonged use of materials are of interest. Material cascading, i.e. the continued reuse of materials through open and closed loop recycling has been covered in numerous publications, where many use LCA (McLaren et al., 2000; Mellor et al., 2002), emergy (Yang and Lay, 2004) or energy indicators (McLaren et al., 1999) to asses the performance and benefit of these cascades. Yamashita (2000) developed a set of circulation indices, giving an indication of material age and quality and an indication of how much material has been reused, or “cascaded”. Hashimoto and Muriguchi (2004) developed a set of six indicators describing material cycling, applicable to by-products and used products. The indicators span the reuse of used products, recovery of by-products or process wastes and the recovery of used products. However, resource efficiency encompasses more than product and by-product reuse. Using resources efficiently also involves the substitution of fossil fuels with renewable sources, the instigation of take-back policies to facilitate material cycle closure, product design for recycling and the use of biodegradable packaging (Veleva and Ellenbecker, 2001).

Dahlstrom and Ekins (2005) distinguish between material efficiency and energy efficiency, as well as the material productivity of energy. Material (energy) efficiency is the ratio between useful material (energy) output and material (energy) input. Material productivity of energy is defined as the energy invested into a process to obtain a unit of product. Exergy has been suggested as another measure for resource efficiency as it accounts for losses in material quality, not just the degree of reintegration on a mass basis (Amini et al., 2007; Cornelissen, 1997). However, a loss of exergy, or material quality, invariable leads to an increased requirement for virgin material to compensate for the loss of useful “work” that the secondary material is able to fulfil. High resource efficiency as defined by Dahlstrom and Ekins (2005) therefore also indicates high levels of exergy, else the high level of recycling would not be attainable.

Additional indicators are materials input per unit of service (MIPS) and cumulative energy requirement analysis (CERA). MIPS is an indicator that shows how much material is required to deliver a certain product or service. The material input includes all the resources extracted from nature to deliver the product or service during its entire life-cycle. This includes production, use and recycling (Ritthoff et al., 2002). Comparable to MIPS, CERA assesses all the primary energy, or energy equivalents in the case of materials, used to deliver a product or service. The entire life of the service or product is considered: production, use and recycling or disposal.

While these indicators capture the desire to reduce energy use and increase material cycling, the more direct environmental impacts of the network are not measured. Other authors have suggested to consider the renewability of resources and toxicity of emissions in addition to input of used materials, recoverability of products at the end of their use and process efficiency (Dewulf and Van Langenhove, 2005). For the environmental aspect of sustainability LCA indicators offer a comprehensive assessment of environmental impacts (International Organization of Standardization, 1998).

Which of these indicators will be chosen to monitor environmental performance in a network can be a function of the environmental issues affecting the network and/or of the strategies chosen to address the environmental issues. For instance, the release of a heavy metal can be monitored either by measuring its expected harm on the environment (in which case the objective would be to minimise eco-toxicity) or by assessing the effectiveness of a proposed strategy in preventing this impact (e.g. recycle ratio of heavy metal indicating how much material is kept in the network and prevented from dispersing into the environment). However, it is recommended to focus on capturing the issue, as multiple strategies may be able to address his issue and can thereby be compared for effectiveness for a particular network.

Economic indicators: Numerous indicators exist to assess economic performance of facilities and supply chains. For gauging the viability or attractiveness of an investment in a process plant net present value (NPV) or return on investment (ROI) are commonly used (Sinnott, 2001a). In supply chains, NPV and ROI are also considered when determining new additions to a supply chain, but in existing supply chains economic performance is more commonly monitored by cost (e.g. (Persson and Olhager, 2002)) and profit (e.g. (Fandel and Stammen, 2004; Gaonkar and Viswanadham, 2003; Heese et al., 2005)). Economic indicators may deliver different performance depending on whether they are assessed for the network or the part of the network (e.g. organisation or facility). All of these are also transferable to industrial network analysis, however, it has to be carefully considered how the indicator is used. If for instance, NPV is calculated for the network as a whole, it may be attractive to include a facility in the network that is not cost effective but is included because overall the network will operate profitably and the facility provides good performance with respect to other objectives. If the NPV were calculated for the individual facilities then such a network configuration would likely not be considered because the unprofitable facility would either be closed down or not be built, depending on whether this facility already existed or was only planned. This phenomenon can also apply to non-economic indicators. In such cases, if network performance can be improved if cooperation of a node, possible interventions should be identified which may help overcome the barrier. To continue the previous example, the facility that would improve performance with respect to one or more objectives could possibly receive subsidies. For a discussion of barriers and means to overcome these, Chapter 2 should be revisited.

Social indicators: Creating reliable social indicator models remains a challenge. The problem with social indicators is that they are firstly difficult to quantify (for instance, how does one measure the degree of a worker’s job satisfaction). Even if they are somehow quantifiable (for instance, by reporting the number or fraction of employees that define themselves as content), social indicators are often not predictable due to the underlying complexity of human motivations, feelings and interactions. There exists therefore a lack of models capable of adequately correlating network behaviour to impact on the workforce, the community and governance. It is however possible to obtain an indication of social performance through the use of proxy indicators. For instance, (and once again in the context of the case study of Chapter 8) “benefit to community” can be estimated as the number of new houses which receive electricity as part of a rural electrification project.

A number of indicators spanning economic, social and environmental performance may be chosen to get a comprehensive picture of whether a sustainable development strategy does indeed promote sustainable development in an industrial network. Indicator scores may also be aggregated into a single score that is easier to deal with than a large set of scores. Using techniques that aggregate indicator scores into a single value is however not particularly desirable. The reason for this is that a change to the network state will in all likelihood alter the performance of some or all of the objectives, and while performance in one aspect may be improved, this may not be the case for the other objectives. How and to what extent the influence of changes is reflected, and more importantly in the objectives depends on how the objectives are assessed, i.e. what indicators are included, and how those indicators are prioritised and aggregated. In the case of a high level of aggregation, insight into the trade-offs will be lost. The trade-offs reflect the degree to which an improvement on one indicator sacrifices performance in another. If a decision-maker would be aware of the fact that a small increase in, for instance, cost could lead to substantial improvement in environmental performance, he/ she may be more willing to make an environmentally favourable decision. On the other hand, if he / she would have to prioritise amongst the objectives up-front a preconception that environmental improvement is costly may mean that he / she values environmental improvement quite low and hence in an aggregation the degree of environmental improvement would be obscured.

5.3 GENERATION OF INDUSTRIAL NETWORK MODELS

The problem structuring should provide a clear picture of what aspects of the network and its environment are to be included for detailed consideration in a quantitative model. The generation of network models is, like the problem structuring, an iterative process, as shown in Figure 5-4. This process consists of the following steps:

1. Scenario generation
2. Data gathering
3. Model development
4. Model execution
5. Identification of preferred network structure and development pathway

The information from the problem structuring will inform what type of data is required. Once the necessary data is available, equations describing network processes, performance, and time-dependent changes can be generated. These models can be examined, repeatedly in the case of multiple scenarios, using the modelling tool of choice. On the basis of this model exploration, it should be possible to identify strategies and preferred network structure and development pathway(s), for the specific sustainable development objectives to be pursued. If any issues are identified, such as lacking data, or interesting network behaviour that should be explored further through additional scenarios or changes to the network model, then the appropriate stage in the network analysis methodology should be revisited.

5.3.1 Scenario Generation

Scenarios are "*focused descriptions of fundamentally different futures*" (Schoemaker, 1993). Scenarios are then used to evaluate and compare network responses and performance, as well as the robustness of network structures and development pathways, and the effectiveness of different sustainable development strategies.

The process of generating and using scenarios for strategic planning in the face of uncertain futures was developed in the 1980 by Royal Dutch Shell (Wack, 1985a, b). "Scenario planning" serves to find a balance between over- or under-estimating change (Schoemaker, 1995). Scenario planning can also guard against common flaws in decision-making such as overconfidence and bias (Schoemaker, 1993). The value of scenarios therefore lies less in their ability to predict the future, but in the insights they provide (Darton, 2003; Schoemaker, 1993). While scenario planning originated from economic strategy planning, the practice of using focused descriptions of different future developments has been widely used in science. The major benefits of scenario analysis were found to be increased understanding of key uncertainties, greater robustness of decisions, but also the potential to incorporate alternative perspectives (Peterson et al., 2003). While these benefits were found in conjunction with biological conservation problems, these benefits are by no means restricted to this area and apply to industrial network analysis as well.

Scenario analysis is an attractive means of considering uncertainty because it spreads uncertainty across various scenarios, rather than analysing the whole range of uncertainty within each one (although this can be done) (Schoemaker, 1995). This is useful for understanding and learning about complex networks, as scenario analysis breaks a problem down into mentally tractable chunks (Chermack and van der Merwe, 2003). For instance, in an optimisation problem, scenarios could be included in a single model, hypothetically, allowing the optimisation to choose the network structure and development that performs best with respect to the chosen objectives for all expected scenarios. However, the optimisation would then not supply any information about why the other options were rejected, and how their performance would compare. For instance, in a comparison of fossil energy options for power generation, how much more CO_2 emissions could be averted if integrated gasification combined cycle technology were to be used compared to conventional steam cycles. As a result it is preferable to divide choices concerning network configuration into discrete scenarios to enable comparison. The increased amount of information supplied by a range of scenarios also contributes to a better understanding of how the network operates, and how performance is affected through technology and linkage choices.

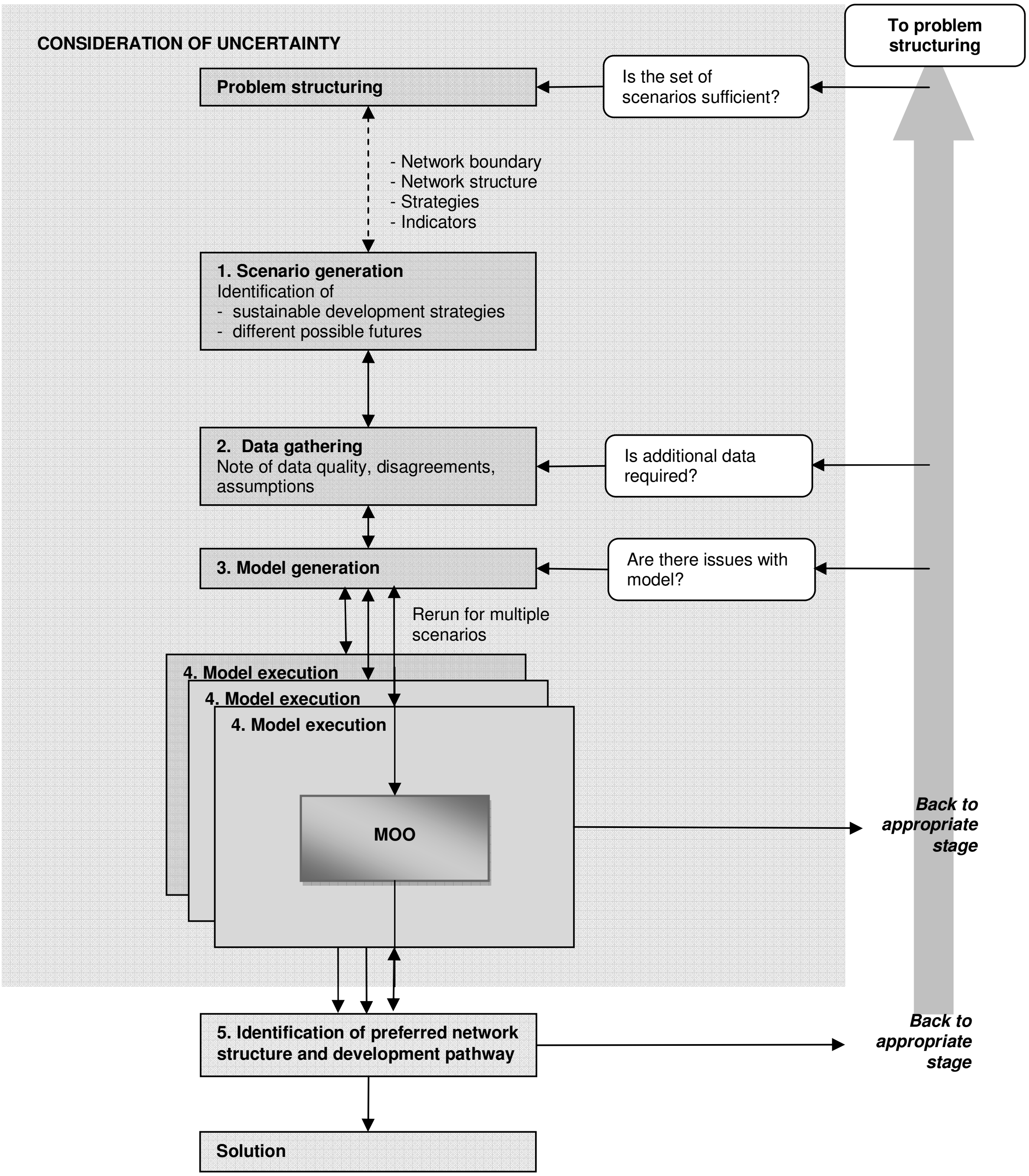

Figure 5-4 The quantitative analysis stage involves the generation of the industrial network model and identification of preferred solutions

The robustness of a sustainable development strategy may be determined by if, and how much, the network response differs between each of the scenarios. Scenario analysis has been used extensively in literature to assess robustness of strategies, for instance in planning for design of material recovery facilities (Chang et al., 2005), to explore the viability of cathode ray tube recycling infrastructure under different disposal patterns (Linton et al., 2002), the effectiveness of different closed-loop supply chains

(Schultmann et al., 2006), and for landscape management under different food chain scenarios in Austria (Penker and Wytrzens, 2005). Once various scenarios have been explored, it is also possible to choose those that deliver preferred performance and proceed to a more detailed analysis. This approach was used to evaluate and rank power expansion options in South Africa (Heinrich et al., 2007).

Scenario generation is explicitly included in the industrial network analysis methodology of this thesis for the reason that the fundamentally different nature of different scenarios will impact subsequent quantitative analysis. The case study of Chapter 7 examines the resource efficiency of wood waste materials. It may for instance be decided to evaluate the effect of using a particular wood waste as a fuel and to compare this to a scenario where the waste is integrated in another network as structural material. In these cases the network boundary would differ in that different facilities would be included. The performance of the respective networks would also differ, due to the different facilities and different products. The boundary definition stage (section 5.2.2) may therefore have to be revisited.

5.3.2 Data Gathering

The outcomes of the problem structuring should provide a clear picture of what information is needed to adequately populate the model/s. This includes a detailed description of

- the scenarios
- the network scope (both temporal and spatial) and structure, including the facilities, technologies and materials and energy
- the sustainable development strategies
- the performance indicators.

These aspects have to be explicitly considered in the industrial network model, but may to some extent be shaped by consideration of the network environment, such as what policies exist and what the objectives of the network agents are.

The consideration of industrial networks is a multi-scale problem, ranging from processes to economic and political influences. The network is described by firm and plant production data (Figure 5-5). Figure 5-5 shows a characterisation of the data required for constructing industrial ecology models based on the scale of application (Diwekar and Small, 2002). The information required for industrial network analysis models depends on the scenarios, network scope, strategies and indicators, but also on the aim of the particular case study and the level of detail adopted. For instance a multilevel model integrating models of the process systems into a meta-model of the industrial network would require both process unit data, but also data at the level of the national economy, as this influences assumptions about network conditions and future.

Data gathering is a combination of literature review for more general information form the public domain relevant to the project, and the consultation with the network agents to obtain context specific and potentially confidential information. The consultation can be in various forms, ranging from surveys, workshops and discussions. Their experience within the facilities included in the model will not only provide a valuable source of information regarding the specific process performance, they will also be able to contribute ideas towards possible opportunities for material and heat integration, i.e. improved environmental sustainability in addition to those that could be identified from a listing of the available wastes and by-products and the possible receivers of this waste and by-products. This approach has successfully been employed to analyse industrial ecologies in Western Australia's Kwinana Industrial Estate (Beers, 2006).

While collecting information, careful note should be taken of conflicting data sources and technology recommendations and of ranges in values where the exact value of quantities is unknown. This is important for uncertainty assessment (see Chapter 6).

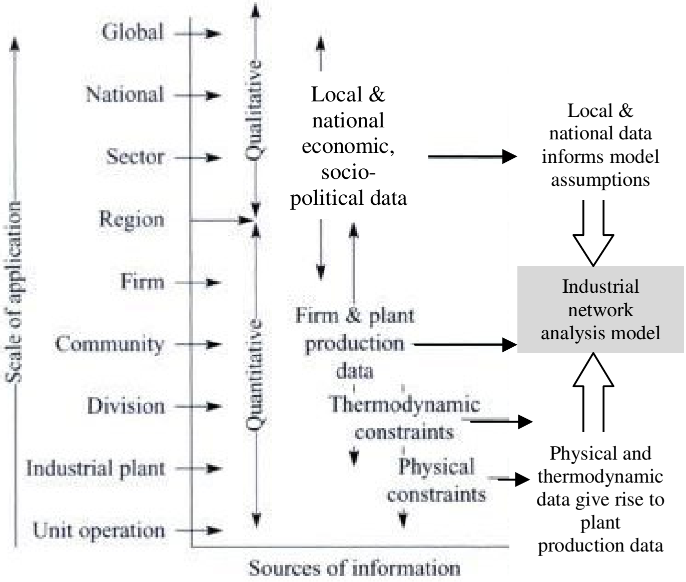

Figure 5-5 Data gathering required based on the network detail considered (adapted from on Diwekar and Small (2002))

5.3.3 Populating an Industrial Network Model

Figure 5-6 shows the outline of the generic life-cycle based industrial network model. All processes from resource harvesting/mining to landfiling and/or open loop recycling are included, as well as closed loop reintegration opportunities. Depending on the network, there may be several life-cycles, open loop and closed loop reintegration options considered. These connections represent material flows (or energy, should this be a nodal product or by-product).

The fundamental building block of the industrial network models are material (and energy) balances around each node. The industrial network can be represented by a set of nodes with specific functions. These functions involve processing, which will determine what integration options exist, and what patterns of distribution, use, collection and disposal prevail. Most of the nodes are likely to represent already existing facilities, but the set can be extended, if additional facilities and/or technology upgrades are seen to be necessary or identified as potentially bringing further benefit, they will be added as additional nodes in the model. The nodes can be grouped into sets according to their function:

Functional sets

$\boldsymbol{a} \in \boldsymbol{A}$	Resource sources	5-1
$\boldsymbol{p} \in \boldsymbol{P}$	Primary processing (processing and refining)	5-2
$\boldsymbol{s} \in \boldsymbol{S}$	Secondary processing (forming and assembly)	5-3
$\boldsymbol{d} \in \boldsymbol{D}$	Consumers / markets (use phase)	5-4
$\boldsymbol{c} \in \boldsymbol{C}$	Collection for reintegration	5-5
$\boldsymbol{l} \in \boldsymbol{L}$	Network sinks (landfill, open loop recycling, export markets)	5-6
$\boldsymbol{r} \in \boldsymbol{R}$	Reprocessing facilities	5-7

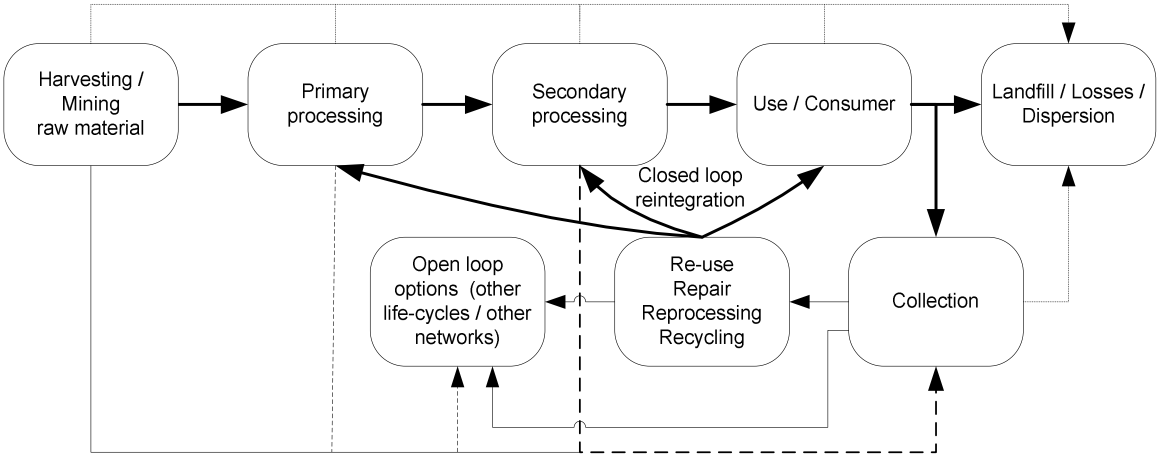

Figure 5-6 Outline of generic industrial network

Apart from the physical nodes in the network, the time frame of the analysis is set to discrete steps and represents an additional set:

$\boldsymbol{t} \in \boldsymbol{T}$ Time horizon 5-8

The number of elements in each set depends on the scale of the network, such as the number of products under consideration and the geographic and temporal scope of the network. While not all of the included nodes may represent viable options it is best to include an extensive network to increase the number of possible options for the optimisation. Viable means that the nodes deliver performance that falls within acceptable ranges, e.g. a facility should be profitable, or its emission levels should not exceed a given limit.

In some cases it may be convenient to further subdivide the sets in 5-1 to 5-7, for instance if one facility has the choice between a range of different technologies or processes, or if a facility has multiple production lines with different specifications. One or more of the sets in 5-1 to 5-7 can thus have the corresponding subset

Process/technology subset $\psi \in \Psi$ 5-9

Industrial networks commonly circulate multiple materials and products. The range of materials is represented by a material set, which will identify what products or materials can be allocated to certain nodes.

Material set $m \in M$ 5-10

This material set can be extended by a material property set. This would be applicable if materials are circulating, where there is a ranges of characteristics, such as degree of deterioration or contamination. These characteristics would influence re-integration opportunities. Alternatively, instead of adopting this additional set, the material set can be extended to encompass the range of characteristics. For instance, material m1 could be new paper which could be recycled, whereas m2 could be recycled paper which cannot be recycled further. With the property subset, both streams would be seen as one material (paper), but with different properties (new/used). In this discussion the material properties are explicitly considered.

Subset of material properties $\varphi \in \Phi$ 5-11

5.3.3.1 Material balances

Material balances provide the fundamental building blocks of industrial network models. Overall, materials in the network can be represented by

$$x_{i,j,\psi,m,\varphi}(t) \tag{5-12}$$

Where *i* and *j* can represent any node in the network from any of the functional sets and describe the direction of material flow between nodes, ψ is the technology, m is the material and φ the property. If *i* and *j* are the same, then this would constitute internal recycling within a single node, or between nodes with common function, such as two different primary processors.

The flows in the network are constrained. The material flow can be *0* if no connection exists between two nodes, or if the connection is not utilised. Else the material flow can only be positive.

$$x_{i,j,\psi,m,\varphi}(t) \geq 0 \tag{5-13}$$

In some cases the flow may be constrained additionally, for instance if a certain demand has to be achieved (5-14) or if capacity limitations cap the amount of material that can be accepted by a node (5-15). The demand constraint will apply to the consumer nodes, whereas the capacity limitations apply to any of the processing nodes. This includes all functional sets except the consumers, *D*.

$$x_{i,j,\psi,m,\varphi}(t) \geq Y_{j,\psi,m,\varphi} \tag{5-14}$$

$$x_{i,j,\psi,m,\varphi}(t) \leq Y_{j,\psi,m,\varphi} \tag{5-15}$$

Source: The material sources deliver renewables, such as forests, plantations for biomass and wind turbines, solar panels and dams for renewable energy. Non-renewable sources would include mines, oil and gas fields etc. Each source can provide a maximum amount of material at time *t*.

$$H_{a,m,\varphi}(t) \geq x_{a,p,m,\varphi}(t) \tag{5-16}$$

$H_{,a,m,\varphi}(t)$ is the stock of material *m* and property ψ available, i.e. mined or harvested at any time *t* at source a.

Primary and secondary processing: The raw material from the source nodes is converted into other materials in the primary, potentially also secondary (tertiary etc.) stages. At these stages either the material is converted (e.g. ore to copper, coal to energy, equation 5-17), or the material properties (e.g. copper is converted into copper pipes, equation 5-18). How this conversion takes place is highly dependent on the technology used at the facilities[16].

$$x_{p,s,m2}(t) = f_p\big(x_{a,p,m1}(t)\big) \tag{5-17}$$

$$x_{p,s,m,\varphi 2}(t) = f_{p,\varphi 1}\big(x_{a,p,m,\varphi 1}(t)\big) \tag{5-18}$$

In this case m_1 (φ_1) is converted into m_2 (φ_2). f is the function describing how the input material (or material property) is converted into product.

If different technologies for a particular processing node are to be explored during the analysis, the equation 5-19 would have to be used (shown only for material property conversion). The choice between the technologies would be represented by either 1, if the technology is active, or 0 if it is not chosen. This variable regulates the allocation between technologies, being equal to *1* if the technology is active, *0* if it is not used. If *np* technologies are available

$$x_{p,s,m,\varphi 2}(t) = Z_{np} * f_{p\psi\varphi 1}\big(x_{a,p,\psi n,m,\varphi 1}(t)\big) \tag{5-19}$$

If one technology is active, the other(s) would have to be inactive, meaning that the sum of Z_n for all technologies under consideration could not exceed *1*. Z could also take any value between 0 and 1 if both technologies could be used simultaneously, in which case Z would represent the fraction at which the material stream is split between the technologies. Such a case is assumed to be rare, though it is increasingly of interest in the minerals processing industry (Stewart et al., 2003). $f_{p,\psi,\varphi}$ is the function representing the conversion of the stream property φ by the process p and technology ψ.

Over the entire node of process *p*, the material balance will have to achieve closure, in other words when summed for all materials and material properties, the material entering *p* at time *t* has to equal the amount departing.

$$\textstyle\sum_a \sum_m \sum_\varphi x_{a,p,}\,(t) = \sum_s \sum_m \sum_\varphi x_{p,s}\,(t) \tag{5-20}$$

Inventory stocks are assumed to be negligible in the processing nodes, as manufacturing is tending towards lean production and just in time delivery to avoid costs associated with keeping high levels of inventory. Should there be an exception, the accumulation of material *m* of property φ in the network will be the difference between all material of that property entering form resource nodes a and the material leaving for the secondary processing nodes *s*:

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[16] If one set technology is used, it is unnecessary to include the technology index.

$$\frac{dSt_{a,m,\varphi}}{dt} = \sum_a x_{a,p,m,\varphi}(t) - \sum_s x_{p,s,m,\varphi}(t) \qquad 5\text{-}21$$

Equations 5-17 to 5-21 are directly transferable to secondary (tertiary etc.) processing, should such a step be included in the network.

Consumer: Unlike the processing nodes, the consumer node is unlikely to practice material conversion. Instead in this stage it is more likely that material properties change through use. The characteristic feature of this node is that 1) it drives the network through its demand for products and 2) it potentially accumulates significant stocks, unless the materials circulating are short lived compared to the time increment of the model. Paper for instance, which is used for a few days or weeks will not show significant accumulation if the model time increment is in years. Material accumulates in the use phase *d* if the material leaving for all collection nodes *c*, or are directly transported to all network sinks *l* or reintegration options *r* is exceed by the input.

$$\frac{dSt_{d,m,\varphi}}{dt} = \sum_s x_{s,d,m,\varphi}(t) - \sum_l x_{d,l,m,\varphi}(t) - \sum_c x_{d,c,m,\varphi}(t) - \sum_r x_{d,r,m,\varphi}(t) \qquad 5\text{-}22$$

These material stocks are an important material source for potential closed or open loop reintegration, but impact the reintegration through the timing of release and the quality of the material. If a material property would change during use, for instance through contamination or deterioration, equation 5-22 changes to:

$$\frac{dSt_{d,m,\varphi}}{dt} = \sum_s x_{s,d,m,\varphi}(t) - \sum_l x_{d,l,m,\varphi}(t) - \sum_c x_{d,c,m,\varphi}(t) - \sum_r x_{d,r,m,\varphi}(t) - \sum_s f_{d,\varphi}\left(x_{s,d,m,\varphi}(t)\right) + \sum_s g_{d,\varphi}\left(x_{s,d,m,\varphi}(t)\right) \qquad 5\text{-}23$$

Where *f* is the function representing material with property φ that changes to another property and g signifies the generation of material with property φ. This can for instance be the fraction of the material *m* that changes property. An example of this would be items entering as "uncontaminated" and leaving as "slightly contaminated" to "very contaminated" (this could be expressed in appropriate quantitative terms), thereby constraining where this material could be reintegrated.

Collector: The function of the collector would be to sort waste in order to pass it on to appropriate (re-processing) nodes or open loop options, i.e. other options lying beyond the boundary of the industrial network. Consequently the collector does not alter the materials or material properties. Stock formation is also possible at this stage, depending on the demand for the waste material.

$$\frac{dSt_{c,m,\varphi}}{dt} = \sum_d x_{d,c,m,\varphi}(t) - \sum_l x_{c,l,m,\varphi}(t) - \sum_r x_{d,r,m,\varphi}(t) \qquad 5\text{-}24$$

Reprocessing facilities: In some cases reprocessing may be necessary before the material can be used to substitute virgin raw materials. In this case the material or material property would have to be upgraded. The material can come directly from the user *d* or from the collector *c*, and is sent either back to the user *d*, to the appropriate processing facilities *p,s*, or to the open loop recycling, *l*. In this node too, there may be *nr* technology choices for the conversion.

$$Z_{nr} * \left[f_{r\psi\varphi 2}\left(x_{c,r,m,\varphi 2}(t)\right) + f_{r\psi\varphi 2}\left(x_{d,r,m,\varphi 2}(t)\right)\right] = x_{r,d,m,\varphi 1}(t) + x_{r,p,m,\varphi 1}(t) + x_{s,r,m,\varphi 1}(t) + x_{l,r,m,\varphi 1}(t) \qquad \text{5-25}$$

Where $f_{r,\psi,\varphi}$ is the function describing the conversion of material property φ_2 back to property φ_1.

5.3.3.2 Performance

In order to accommodate the dynamic behaviour of the network, the performance of the network is assessed by allocating the impact of each node directly to its product stream. If there is more than one product stream the environmental, economic and social burdens can be divided according to the LCA methodology: In the case of multiple product streams the impacts are allocated according to weight, economic value, or according to some other property of the product (Azapagic and Clift, 1999a; Ekvall and Finnveden, 2001), where the chosen property has to be accounted for in the model. The impact is then summed over the entire network, and over the assessment timeframe. This will give a total absolute score for each individual indicator for the network over the analysed time frame.

$$E = \sum_t \sum_i \sum_m E_{i,m}(x, \Theta) \qquad \text{5-26}$$

where the network performance with respect to indicator *E* at any time *t* is a function of the flows *x* and other network parameters *Θ*. Each node *i* and each material *m* may contribute towards the network performance.

5.4 MODELLING APPROACHES

In the preceding text the steps of the problem structuring and the generation of network models were described in detail. These mathematical models are used to explore the effectiveness of strategies, and the network structures and development recommended under these conditions. In Chapter 4, optimisation, specifically multi-objective optimisation (MOO), was chosen as the most suitable modelling approach for this intent. Within MOO, multiple approaches exist as to how several potentially incommensurate and/or conflicting objectives may be considered simultaneously. These are discussed in this section.

5.4.1 Multi-objective Optimisation

The optimisation of time-varying industrial networks with respect to multiple objectives makes it necessary to perform dynamic multi-objective optimisation (MOO). The general form of a MOO problem with linear and nonlinear constraints is:

$$\min_x \{f_1(x), f_2(x), \ldots, f_n(x)\} \qquad 5\text{-}27$$

Subject to

$$c(x) \leq 0 \qquad 5\text{-}28$$

$$ceq(x) = 0 \qquad 5\text{-}29$$

$$A \times x \leq b \qquad 5\text{-}30$$

$$Aeq \times x = beq \qquad 5\text{-}31$$

$$lb \leq x \leq ub \qquad 5\text{-}32$$

c(x) and *ceq(x)* are nonlinear equality and inequality constraints, *A* and *Aeq* are the coefficients for the linear constraints and *b* and *beq* the associated right hand sides. *lb* and *ub* are the lower and upper bounds on the set of decision variables, *x*. *x* is time varying in this case and some or all of the constraints or objective functions, i.e. parameters or function form, may vary through time. Most of the decision variables are material flows; however, they may also, for example, represent capacities or the choice between two technologies or locations, in which case binary variables would be used that activate or deactivate the appropriate technology/location. The material balances and conversion equations (equation 5-12 to 5-24) serve as the constraints (equations 5-27 to 5-31). The set of functions ($f_1(x)$, $f_2(x)$ …) represent the objective functions measuring the performance of the network. These are the indicators defined by equation 5-25.

A number of different approaches to MOO exist, which are also valid for dynamic MOO. Most of these rely on scalarisation, which means that the set of objective functions is converted into a problem with a single objective function or a family of single objective functions. MOO methods have been classified into generating and preference-based methods Cohon (1985). In generating methods, the Pareto optimal solution is generated for the decision-maker, who then chooses the final solution. In preference-based methods, the decision-maker's preferences are taken into account during the solution process. Miettinen

(1999) categorised these methods further according to according to the involvement of the decision-maker which was first presented in Hwang and Masud (1979)[17]:

- no-preference methods,
- *a priori* methods,
- *a posteriori* methods
- interactive methods.

This classification is not absolute. Overlap and combination of approaches is possible, which can belong to more than one class.

As the name implies, in no-preference methods no articulation of preference is used. Instead, some relatively simple method is used to obtain a solution that is presented to the decision-maker, who can then either accept or reject it. These methods are suitable in situations where the decision-maker has no special expectations, as they are unlikely to find a solution that best satisfies a decision-maker.

In *a priori* methods, the decision-maker has to specify his preferences before the solution process. A decision-maker at this stage would be unaware of the trade-offs possible between objectives. It has also been stated that value judgements should be excluded from explicit encoding when evaluating environmental decisions (Basson and Petrie, 2007b).

A posteriori methods generate the entire Pareto optimal solution set before presenting it to the decision-maker for further evaluation. *A posteriori* methods have the benefit that they do not make any value judgements before a solution is chosen. These methods are more computationally expensive, but they have the benefit that the decision-maker can see what the trade-offs are among the different objectives. This knowledge may influence the choice of the decision-maker: If he becomes aware that, for instance, a small increase in cost can yield a substantial decrease in environmental impact, then the decision-maker may be willing to adjust his/her relative preferences. However, it can be hard for the decision-maker to make a decision in the face of the large number of alternatives.

Interactive methods involve a progressive articulation of preference information from the stakeholders or decision-maker. This is the most developed of the four classes. Many of the weaknesses of no-preference, *a priori* and *a posteriori* methods can be overcome through the continuous engagement with the decision-maker and stakeholders. Only part of the Pareto surface can be generated, and the decision-maker can correct his preferences as he gets to know the problem and the trade-offs better. However, most approaches assume that decision-makers' responses are consistent, which they often are not. Some of the

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[17] Miettinen (1999) addressed nonlinear MOO specifically, however, these methods are also applicable to linear, nonlinear and integer problems.

interactive approaches are sensitive to inconsistencies and therefore means have to be included of dealing with these inconsistencies, such as consistency tests.

For large-scale problems, hierarchical approaches have been developed, which are reviewed by Haimes and Li (1988). These methods use the "conventional" MOO methods but decompose the system into smaller subsystems to make it tractable. Methods applied to large-scale problems are further presented in Haimes et al. (1990) and Tabucanon (1988).

Based on the discussion of the four approaches, interactive approaches appear to have the greatest benefit, provided the decision-maker has the time and capabilities to be sufficiently engaged in the decision making process. Should this not be the case, *a posteriori* methods are also attractive, as they allow more insight into the problem before a decision is required than no-preference and *a priori* methods. For these reasons, the ε-constraint method, an *a posteriori* method, was used in this thesis.

5.4.1.1 The ε-constraint method

The ε-constraint method is one of the most widely used methods and can handle a variety of problems[18]. It is computationally demanding, but it has the advantage of handling even duality gaps in non-convex problems (Miettinen, 1999). It is also not necessary to check the uniqueness of the solution with this method, which is demanded by other theorems (Miettinen, 1999).

The ε-constraint method can be used to create a Pareto surface by retaining one function for optimisation and converting all others into inequality constraints.

$$\min_x \; f_l(x) \tag{5-33}$$

$$\text{subject to } \; f_l(x) \leq \varepsilon_j \; \text{ for all } \; j = 1, \ldots n, \; j \neq l, \; x \in F$$

where F is the feasible region

The parameters, ε_j are determined through the use of a payoff table. To generate such a table, all objectives are first optimised individually, determining the best performance for each and the associated decision variables. For each set of decision variables, or decision vector, the performance in the remaining objective functions is calculated. Row i of the payoff table then shows the values for all the objectives when f_i is optimised. The diagonal of this table thus provides the values for the ideal objective vector. The worst performances in each row i estimate the nadir objective vector. The best and worst performances for each objective function j are then the upper and lower bound for ε_j. The distance from lower to upper

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[18] This method also forms the basis of many of the interactive methods.

bound is then divided into discrete sections. How many sections are required is not covered in the general optimisation literature (Diwekar, 2003; Miettinen, 1999). The greater the number of sections, the greater the computational effort, but the more detailed the resulting Pareto surface becomes as well. It is therefore important that a large number of intervals are generated. However, what number of intervals is sufficient depends on the shape of the surface. More complex surfaces require a greater "resolution", while simpler surfaces can be adequately portrayed even if points on the surface are only determined at few intervals between the upper and lower bounds of ε_j. However, as it is not always possible to know in advance if a surface is complex, it is advisable to start use the greatest number of intervals that can be solved in a feasible amount of time. The single objective function $f_l(x)$ is then optimised repeatedly, as all those objective functions converted to constraints step a chosen, discrete number of times from lowest bound, to highest. If the step size is small enough, the Pareto surface can be determined.

A step-by-step explanation of how to apply this method is given in Appendix B. Figure 5-7 illustrates the process for generating the Pareto surface using the ε-constraint method. Also shown is the combination of software programs used. The optimisation was performed in GAMS[19], a popular and powerful optimisation software. However, due to limitations in graphical and data manipulating capabilities beyond solving optimisation problems, data and results have to be exported to Excel to create pay-off tables. With the bounds from the pay-off table the optimisation problem is rerun to construct the Pareto surface. Depending on the solver used it may be necessary to screen for infeasible results.

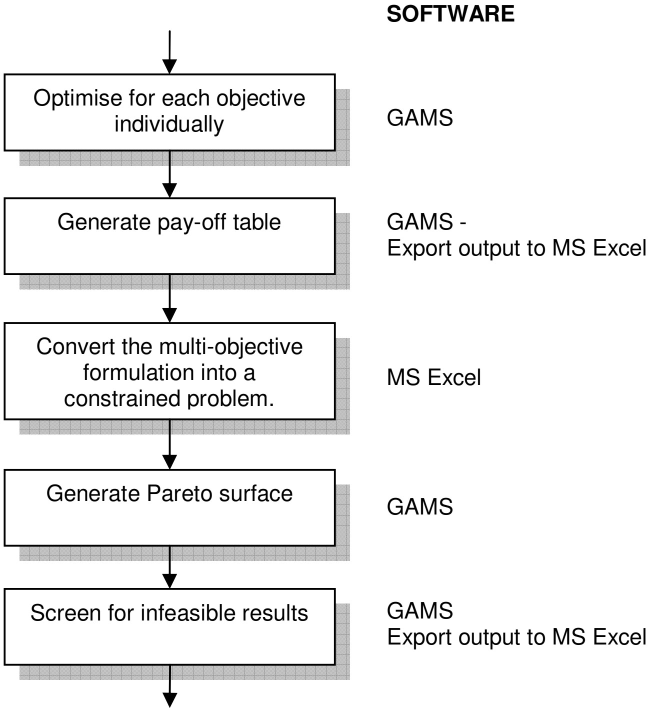

Figure 5-7 Outline of steps for the execution of network models using MOO

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[19] www.gams.com/

In this thesis, the approach will be demonstrated for no more than three objectives. This is deemed sufficient to demonstrate the industrial network analysis approach. However, with three or less objectives, a Pareto surface can be shown graphically and trade-offs between objectives discussed to determine a preferred solution, i.e. one that delivers acceptable performance with regards to all objectives. For four or more indicators only partial representations of the surface would be possible and comparison and trade-off between objectives would become increasingly challenging. Under these circumstances identifying a single preferred strategy may require some form of ranking and trading-off amongst the objectives. This can be facilitated by so-called programming or satisficing methods, or multi attribute decision making methods (Belton and Stewart, 2002). These methods will not be engaged with here, but would constitute a valuable extension of the industrial network analysis methodology.

5.4.1.2 Limitations of Optimisation

With regards to the optimisation in particular, there are also still general limitations that may affect the application of this approach to very large, complex industrial network models.

- **The efficient computation of system models**: In optimisation problems the computation increases exponentially with problem size. There is thus a requirement for efficient algorithms. If such algorithms cannot be, or have not been, developed then usually a good heuristic can be used instead. Ahmed and Sahinidis (2000) proved that process planning problems (which are mixed-integer problems) that efficient algorithms for their solution are unlikely to exist, but that reliable heuristics can be developed. Solution of problems within reasonable amounts of time is especially important for use in real-time situations, such as the use of models for process control.
- **The identification of global optima** in the case of large-scale non-convex[20] non-linear programming (NLP) and mixed-integer non-linear programming (MINLP) problems remains a challenge. Genetic algorithms and branch and bound methods, among others, are used in an effort to minimise the possibility of getting stuck in local optima. The larger the model the more difficult this process becomes, as the curse of dimensionality also affects the number of local minima. There are algorithms that can sample the decision space (tabu search, evolutionary algorithms) but these are time intensive and can still not guarantee that a solution found is a global optimum.
- **Optimisation under uncertainty**: An explicit consideration of uncertainty in industrial network models, for instance through stochastic programming as described in the previous chapter, has a tendency to rapidly increase not only model size, but also the mathematical complexity. This increases the difficulty of solving such problems, or solving them in reasonable time. This again raises the issue of having efficient computation of system models.

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[20] Convexity is a property of functions that determines whether they have a single global minimum (a function has to be concave to have a single maximum), in which case a globally optimal solution can be found. A non-convex function has multiple local optima, in which case a global optimum cannot be guaranteed. More on this can be found in Appendix B.

However, these are challenges to optimisation research in general and are unlikely to be resolved in IE. Once they are resolved, industrial network analysis would become more powerful, and better equipped to identifying preferred network development pathways for complex industrial networks.

5.4.2 Motivation for Choice of Software

Industrial system models have the following features that need to be considered in the choice of software:

- They are composed of a large set of variables, some of which may be integers.
- They are dynamic.
- There are multiple objectives, and some of the objective functions may be non-linear.
- It has numerous linear and non-linear constraints.
- The models represent complex systems, and the chosen software should be flexible enough to handle the variety of processes, materials, relationships and other influences that characterise the performance of these systems.

Despite an optimisation toolbox to extend its capabilities, Matlab still has limitations on the type of optimisation problems it can be applied to. Compared to this, dedicated optimisation languages like LINGO, AMPL (Another Mathematical Programming Language), AIMMS, GAMS (General Algebraic Modeling System), gProms or ISIGHT, have libraries of algorithms to choose from to best fit the specific problem. GAMS is extensively used by the PSE community for optimisation (e.g Vecchietti and Grossmann (2000)). GAMS was therefore chosen as the optimisation software used for this thesis. Problem coding is more straightforward than it is in Matlab. Written in GAMS, a problem requires about half the code it would take to model the same problem in Matlab, as the equations describing system behaviour do not need to be entered into matrices. As a result GAMS models are also easier to read than Matlab models, which makes error checking and model alterations easier. GAMS has two disadvantages: a) It is text oriented, so output of results may need to be exported to other program to display and analyse, and b) it is exclusively algebraic, so it cannot handle differential equations, unlike AMPL or gProms. Both of these problems can be overcome. GAMS can be linked to programs with more sophisticated graphical representation capabilities, such as Matlab or Excel, where the graphs can then be generated. The second, more important concern can be overcome by dicsretisation of the problem and integration where possible.

5.5 VALIDATION OF INDUSTRIAL NETWORK MODELS

One of the major problems with the analysis of industrial networks is model validation. Process plants can now be designed, analysed and controlled to a point that models match real plant performance with good accuracy. In the higher scale systems, such as SCM and IE, and in macro–economic models too, validation is seldom explicitly addressed. The problem with industrial networks is firstly, that they are under distributed control and subject to constant interaction with a changeable environment, hence network behaviour is not necessarily consistent enough for empirical validation. Secondly, the introduction of sustainable development strategies changes the existing network, provided one already existed. The validation of hypothetical networks is naturally more difficult and some authors would even argue that validation of non-existent models is impossible (Persson and Olhager, 2002).

It has to be kept in mind that models of complex systems such as industrial networks can only ever be approximations (Kremer et al., 2006). However, the validity of a model can be increased by adhering to the following points in as far as possible (Balci, 1998; Law, 2005; Law and Kelton, 2000):

- Providing a definitive problem formulation,
- discussions with network agents, other stakeholders and experts,
- development of a written conceptual model,
- structured walk-through of the conceptual model (*conceptual model validation*),
- use of sensitivity analysis to determine important model factors,
- comparison of model and system output data for an existing system, if possible (*results or empirical validation*).

Law and Kelton generated these points for simulation models. However, the underlying logic applies to any kind of model which aims to capture the behaviour of physical systems. The validation process relies, on the one hand, on a clear statement of what is to be achieved, thereby clearly defining the model's purpose and scope. This is addressed during the problem structuring exercise, which is embedded within the industrial analysis methodology developed here. The other important aspect is the interaction with experts to say whether assumptions are correct and model outcomes are credible[21]. If a model predicts that projects with negative rate of return will go forward, or that, for instance, power is generated when there is no installed capacity then these are obvious signs of mistakes or flawed assumptions. The assumptions and equations that led to this outcome should be re-evaluated. This is also known as *face validation* (Law, 2005). However, a credible model does not necessarily have to be valid, and *vice versa*. Especially in complex network models, an optimisation may deliver counter intuitive results that have to be carefully examined to determine if cause and effect make sense. It is important that validation takes place

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[21] A model and its results have credibility if the decision-maker and other key project personnel accept them as "correct."

continuously throughout the model building. If it is done afterwards, already completed work may have to be revisited and repeated, causing extra effort. The fact that the industrial network analysis methodology described in Figure 5-1 and Figure 5-4 is an iterative approach, where, after each step, critical questions about the outcomes have to be answered, and, if necessary, preceding stages revisited, is a process of validation.

A structured walk-through is another approach to increase both the validity and credibility of the model (Law, 2005; Persson and Olhager, 2002). A structured walk-through involves consultation with experts, decision-makers and stakeholders to walk, or rather talk, them step-by-step through the model, discussing how the network is to be captured and the assumptions underlying model development. In the industrial network analysis methodology, the walk-through is best conducted at the conclusion of the problem structuring, possibly during or after the data gathering stage (see Figure 5-4). For a network it may be difficult to find people with intimate knowledge of the entire network, however, stakeholders may deliver information about their area of expertise in the network.

5.6 CONCLUSIONS

The aim of this chapter was to develop the industrial network analysis methodology by integrating the approaches highlighted as attractive in Chapter 4. In this chapter the industrial network analysis methodology has been introduced, detailing the individual steps, from problem structuring based on MCDA, to the quantitative analysis using MOO. The addition of problem structuring stage has two distinct advantages over immediately launching into a quantitative analysis. 1) Even if influences of the problem context and the network environment are “only” considered qualitatively, the contemplation of the full scope of the situation will beneficially reflect on the subsequent model representation, the way the outcomes are interpreted in the hope of delivering better quality outcomes that are better fitted and reliable for the given context. 2) Problem structuring contributes to the validation of network model by clarifying the issues and making underlying assumptions transparent so that inconsistencies can be readily identified and addressed if necessary. However, while problem structuring allows a thorough exploration of the context, it has to be kept in mind that inevitably not all perspectives, influences and interactions can be known and that interpretations of context influence, the issues and what this means for sustainable development in a network may be flawed. Problem structuring is therefore not a guarantee that the context will be engaged with fully and that assumptions are correct.

Nodal activities are described in industrial network models by overall mass balances that aggregate the detailed nodal function. The models could, however, be extended to include more detailed process models.

This would be attractive in cases where greater detail is required, for instance to obtain insight into operational performance of facilities, or in cases where no empirical data is available to describe overall nodal behaviour with reasonable accuracy, for instance for new processes. The multilevel modelling mentioned in Chapter 4 could be used to include these process models in the network model.

Industrial network analysis is not strictly a linear process where the discussed stages of the underlying methodology are followed and a solution delivered. It was indicated at various stages that the analysis process is rather an iterative one, where the insights from a model run may indicate that additional data is necessary, that the range of scenarios may cause the network boundary definition to be revisited or where stakeholder input makes it necessary to redefine the problem definition. The outcome of the analysis benefits from these iterations, as the quality and comprehensiveness of the process improves.

Industrial network analysis is designed to be flexible in that it can handle any type of industrial network, i.e. facilities linked by material and energy flows. Apart from helping to determine network structures and development pathways that contribute to sustainable development, industrial network analysis could also be used to assess how an individual facility fits in its surroundings and may strategically position itself in its environment, a point which was already raised in the previous Chapter 4. This type of thinking is seen as the way forward in PSE (Grossmann, 2004). However, it is not suitable to apply industrial network analysis to a process or facility. Process plants have different characteristics and operate according to purely technological constraints and rules, with none of the complexities that affect industrial networks. Process plants, for instance, have very limited ability to change their structure during their life-time. The analysis also has limited applicability to strategic planning of material and energy allocation in higher level systems, e.g. within national economies. The level of aggregation in models on the economic scale would result in the loss of case specific information that would allow tailoring of strategies to the specific needs of similar facilities in different settings.

While the flexibility of the approach, i.e. its ability to be “tailored” to a specific situation, is seen as a strength, it may also prevent the outcomes from being reproducible or suitable for comparison with other networks. It is hoped that the focus on the needs of a specific network will lead to more effective strategies, however, it does introduce a degree of subjectivity to the analysis. There is no specific set of indicators or a specific network definition that would ensure a consistent approach for different cases. Should the industrial network analysis be repeated for the same or a similar network with a different set of stakeholders and decision-makers, then the analysis may lead to different outcomes. However, the question is whether different outcomes equate to one outcome being worse or better than another. As long as there is a net benefit by instituting sustainable development strategies, i.e. improved performance compared to the current state or a positive performance with respect to the chosen indicators, then that strategy is still acceptable.

Several limitations were identified. Among them are computational limitations of optimisation. These are unlikely to be solved in the IE research, but are relevant as they constrain the complexity of the model that can, at least within reasonable time and computational effort, be handled. With the development of more powerful computers and better solution techniques, it would be possible to further increase the scope, detail and complexity of the network analysis. A limitation of the industrial network analysis approach in particular is the difficulty determining preferred network structures and development pathways if more than three indicators are considered. Future work should therefore extend industrial network analysis to include ranking and prioritization methods to facilitate the choice of a preferred solution.

Chapter 6 builds up on the work in this chapter. It engages with how uncertainty analysis, which encompasses a number of additional tools, is integrated within this industrial network analysis methodology.

6

CONSIDERATION OF UNCERTAINTY

6.1 INTRODUCTION

Uncertainty[22] in industrial network analysis implies randomness or a lack of knowledge or understanding of all industrial network aspects: its structure, its performance at a given time and in future, how it affects, and will be affected by, its environment. This uncertainty about the network and its environment will enter the industrial network analysis, creating doubt about, amongst other things, how the network is modelled and populated numerically, and the underlying assumptions. Uncertainty therefore raises doubt about the accuracy of the network models, the way sustainability strategies are captured and consequently the reliability of proposed sustainable development pathways for an industrial network. A strategy that works for an expected state of the world may perform sub-optimally or even fail if the actual state of the world is, or will be, quite another. A high degree of uncertainty makes projects appear risky, affecting the desire to invest, timing of investment, and return on investment (Birge and Rosa, 1996). In this context, uncertainty affects the desire to implement a sustainable development strategy, when to implement it and how environmentally beneficial, economically feasible and socially advantageous the outcomes will be.

By explicitly identifying, capturing and handling uncertainty during the industrial analysis process, the effect on model outcomes, and therefore the reliability of assessment results and recommended sustainable

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[22] The term uncertainty is used to both describe a lack of knowledge as well as variability of data. In the case of variability a parameter may be known, but it is likely to change in an unpredictable manner. However, here the term uncertainty is used to encompass both unless stated otherwise.

development pathways, can be ascertained. As a result, decision-makers will be better able to judge the chances of a proposed strategy being an effective one. A sustainable development strategy and associated network structure can be assumed to be effective if

- it is reliable, i.e. consistently performs well, over a range of possible network parameters, or future developments.
- it is robust, or its effect minimally influenced by changes to the expected parameters and futures.

The analysis of uncertainty in industrial network analysis is concerned with measuring the degree to which uncertainties during problem formulation and model development contribute to uncertainties in the output of the analysis. This chapter addresses:

- Where and how uncertainty is introduced in industrial network analysis?
- What are suitable means to dealing with these uncertainties, both qualitatively and quantitatively?
- What effect do uncertainties have on the reliability of the outcomes of the industrial network analysis, and how can decisions to promote sustainable development be made in the face of uncertainty?

The chapter begins with a discussion of the sources of uncertainty that are commonly encountered and consequently considered in analysis in PSE, SCM and in IE. This is followed by a general characterisation of uncertainties in industrial networks models. On the basis of this, means to capture and propagate uncertainty in industrial network models will be addressed.

However, uncertainty in an industrial network may be extensive and may be exceedingly time consuming to consider all uncertainties. Therefore it would be attractive if uncertainties could be screened to identify those that are the most important, allowing a modeller to focus on a reduced set. The final section, 5.8, describes the overall methodology on how the discussed uncertainties approaches are combined within the industrial network analysis.

6.2 CHARACTERISATION OF UNCERTAINTY

In this thesis, uncertainty is classified according to two criteria: where it originates from, and how it is expressed in the system model(s). To indicate origin, Bonano's (1995) classification of technical and valuation uncertainty is used. Technical uncertainty is always present when a physical system is mathematically captured. However, industrial network analysis intends to identify and recommend preferred sustainable development pathways which necessitates value judgements concerning what is desired and important, thereby introducing valuation uncertainty especially during the information structuring aspect of the analysis. (This will be explored in detail in 6.5.1 and Table 6-2). Both technical and valuation uncertainty affect the industrial network analysis model. These uncertainties are therefore further attributed to the data used in the model, or the form of the model itself (Hofstetter, 1998; Morgan and Henrion, 1990).

Uncertainty in empirical parameters: Empirical parameters represent properties of the real world that are measurable, at least in theory and thus have a "true", as opposed to a "best" value. Examples include product prices, technological efficiencies and amounts of pollutant emitted. Empirical quantities are measured are thus inherently uncertain as nothing can be measured 100% precisely. The uncertainty may, however, be negligible. Most attempts to categorise uncertainty have centred on empirical quantities. Morgan and Henrion (1990) classified empirical uncertainty sources as being statistical variation, subjective judgement, linguistic imprecision, variability, inherent randomness, disagreement among experts and approximation.

Uncertainty in model parameters: Model parameters encompass decision variables, value parameters and model domain parameters. Model parameters cannot be said to have uncertainty per se associated with them as they do not have a "true" value, rather model parameters are set by the modeller. However, while they do not have a "true" value, their variation will affect outcomes, and some parameter values may deliver "better" results. For this reason uncertainty in their values has to be considered.

Uncertainty in model form: This refers to uncertainty in the structure or type of the models used. Models are abstraction of reality and as such there will always be limitations to the accuracy and precision with which they capture the real world system. Nevertheless, some may be more applicable than others in a given context. When it is unclear which one is better, a comparison of the discrepancy between the different model outcomes will be useful to judge if a robust decision can still be made.

This classification is similar to some extent to that of the US EPA (US-EPA, 1989) which lists parameter, model and scenario uncertainty, where scenario uncertainty to some extent includes valuation uncertainty by referring to normative choices made during LCA model development. The combination of Bonano's and Morgan and Henrion's uncertainty characterisation has also been used by Basson (2004) and Treitz (2006) to manage uncertainty in environmental decision making. This classification will therefore also be adopted here. The application of this classification to the particular case of industrial network analysis forms another contribution of this thesis. It serves to highlight what types of uncertainties are expected to arise at different stages of the analysis.

The choice of how to represent these uncertainties and which tool(s) to use to propagate them is determined by the type of uncertainty being dealt with. The remainder of this section discusses parametric and model form uncertainties, and details their meaning in the context of industrial networks and industrial network analysis.

6.2.1 Uncertainty in Empirical Parameters

This section gives an outline of the sources of empirical parameter uncertainty in industrial network models, as well as suggestions on how, if possible, it could be reduced. For a more detailed discussion of these uncertainties, the interested reader is referred to Morgan and Henrion (1990).

6.2.1.1 Random error and statistical variation

Statistical variation is the result of measurement errors, which occur with even the most sophisticated measurement devices. The degree of uncertainty is influenced by the number of measurements taken and the size of the variations between observations. The field of statistics has a number of techniques for quantifying this uncertainty, such as standard deviation and confidence intervals. This uncertainty is however expected to play a minor role in industrial network models. Due to the nature of industrial network analysis a high level of abstraction and assumptions will be needed and this is expected to dominate over any uncertainties in measurable data used.

6.2.1.2 Systematic error and subjective judgement

Where random error influences the spread of an uncertainty distribution, systematic error determines how close (or far) the mean of the measured distribution lies from the “true” value of the measured quantity. Systematic error is the result of bias in the experimental procedure and measurement devices. It can have a variety of causes, such as faulty calibration of instruments and flawed assumptions with regards to inferring the actual quantity from the observations. An example of systematic error is inferring how humans would respond to small amounts of a chemical based on the responses lab animals have to large doses of the chemical. Another common source of subjective judgment is the use of historical data to infer behaviour of the same quantity in the future. These judgements, where information from one context is applied to a somewhat different context, can feature prominently in industrial network models, as firsthand data for all aspects of the network, its subsystems and future trends, may not always be readily available.

6.2.1.3 Linguistic imprecision

“The technology has low carbon dioxide emissions” is an example of linguistic imprecision. It is uncertain exactly what qualifies as “low” in this context. It could be that the technology is seen as low if the emissions are lower than the regulatory standard. Others may see emission levels as “low” if the emissions approach best practice levels. A lot of information from industry or expert sources is imparted verbally and through qualitative statements and it is not always amenable to mathematical interpretation. Linguistic imprecision also impacts heavily on the elicitation of stakeholders’ and network agents’ values and perspectives during problem structuring and expert input during model development in industrial network analysis.

Often linguistic imprecision is the result of a quantity being insufficiently specified. A quantity is said to be well specified, if, given complete information, there would be agreement on the value of the quantity. For example, the price of fuel is an ill-defined quantity, as fuel prices vary with location and are constantly changing. The quantity would thus be well specified if it was known where and when the fuel was sold. Even if no exact number could be delivered, being more specific, for instance by saying “The technology emits less carbon dioxide than industry average”, would already reduce the degree of uncertainty. The problem and system boundary definition of industrial network analysis would mitigate the problem of insufficient specification.

6.2.1.4 Variability

This describes parameters that change over time and space. Industrial network aspects such as resource availability and customer demand will be subject to variability in industrial networks. For instance, the amount of hardwood harvested from forests for furniture manufacture is an example of variability, as it will vary somewhat on a daily, seasonal and yearly basis. Variability of certain quantities can be captured well in terms of frequency distributions. In this case one has to remember that frequency distributions do not necessarily have to have uncertainty associated with them. If detailed statistics about logging activities in a particular plantation over the course of a year are consulted, the resulting distribution will be very precise. If one would want to know, however, what the frequency distribution of the flow rate would be in the year 2025, then assumptions will have to be made and the distribution will involve uncertainty again. There is thus a distinction between variability and uncertainty.

6.2.1.5 Inherent randomness and unpredictability

An occurrence or development may appear random if there is no known pattern or model that can be used to determine its cause or behaviour. Rainfall is an example of randomness, as there are so many factors influencing the daily weather that there is to date no model that can accurately predict rainfall more than a few days in advance.

Inherent randomness distinguishes itself from other types of uncertainty in the fact that it cannot be reduced, at least practically. Theoretically, if all factors affecting weather were known, then it would be possible to predict rainfall in twenty year's time. The current state of knowledge makes rainfall a random event in practice, however. In industrial networks, complex behaviour that is difficult to predict and gives rise to apparent randomness in parameters may either stem from agent behaviour, which is however not considered in this thesis, or from developments in the network environment, e.g. the political situation, climatic developments etc.

6.2.1.6 Disagreement

Usually the opinions of scientists reach a consensus on the values of specific measurable quantities after a certain period of research. However, in the cases where information is hard to obtain, or where a subject is approached from different perspectives as is the case in industrial network analysis with stakeholder involvement, this period may be very long and experts may hold quite disparate opinions, creating a quite significant source of uncertainty. Industrial networks and the sustainable development context are both complex and as a result stakeholders, agents and consulted experts will have to base their views on simplified mental models of the complex real world problem. These mental models or views of the problem are thus likely to differ from person to person, inevitably giving rise to disagreement.

There are techniques available to account for differences in opinions regarding uncertain empirical quantities, although it should be noted here that there may be disagreement concerning model parameter setting as well. It is common to combine the opinions by assigning weights to them, but then the chosen values of the weights themselves are uncertain is not accounted for. These weights can be derived from self-rating by the experts, from the experts rating each other, or from the analyst's rating of the information provided based on his subjective judgement by the experts. It may be worthwhile to assess whether the difference in expert opinion on a quantity is significant relative to the uncertainty associated with this quantity. If the difference has a significant impact on model outcome it would be best to not combine expert opinion, but model them separately.

6.2.1.7 Approximation

Simplification and approximation are necessary to make the complex industrial network models tractable and to adjust data from other sources to the context of the model. This affects not only empirical quantities, but also parameter estimation. Assumptions are made in order to set the temporal and spatial domain of the industrial network model, as well as their resolution (influencing domain parameters and index variables). Continuous variables, distribution and functions may be discretised. Each assumption represents a trade-off between model precision and computational cost.

It is hard to assess how much uncertainty is introduced with each assumption. In some cases a theoretical argument can be enough to justify an assumption. In many cases, however, checking the influence of approximation uncertainty would require increasing the detail, scope or resolution of the industrial network model to asses the impact on the model outcomes. As this frequently requires substantial reprogramming it is not often done, yet it would be a useful way of determining the appropriate level of detail for the model. "Appropriate" in this case implies sufficient precision without overwhelming computational complexity. To avoid reprogramming, it is best to go for the greatest level of detail that can reasonably be handled. An overview of the empirical parameter uncertainties discussed here and examples of these are given in Table 6-1.

6.2.2 Uncertainty in Model Parameters

There are different types of model parameters, among them decision variables, value parameters, model domain parameters and defined constants. *Decision variables* are also sometimes referred to as control variables, as they represent the parts of a network, or model of that network, that a decision-maker exercises control over. In the case of industrial network analysis, decision variables cover all the aspects of how any proposed strategy would affect the industrial network. For instance, if a strategy involves linking previously unlinked network units, then the mass flow associated with that link will be a decision variable, as the decision-maker can select its value. Subsequently, these variables can be manipulated (in the case of optimisation by the algorithm) to find a "best" value (which is the reason the model gets constructed in the first place), but they do not have a "true" value. It should be noted that some quantities may sometimes be categorized differently depending on the view point of the stakeholder. For instance, if government decides on emission limits to water for certain chemicals, this is a decision variable for them, but it will be an empirical quantity to any industries releasing those chemicals to water.

Value parameters represent the preferences of the individual stakeholders. Common value parameters are discount rates for costs and benefits accruing over time, or risk tolerance. These quantities often have significant uncertainty associated with them, as a stakeholder would struggle to express preferences in terms of exact numbers. Value parameters are sometimes treated as empirical quantities, but according to Morgan and Henrion (1990) this is generally not acceptable. Value judgements may be based on empirical data, but in the end they are selected based on personal preference. A possible exception, where value parameters can be treated as empirical quantities, is if the values of other stakeholders have to be estimated to predict responses, for instance to model competitors" responses to company policy. In this context the preferences of the decision-maker are value parameters, but the other parties" values should be treated as empirical parameters.

Model domain parameters specify the spatial and temporal domain modelled, as well as the resolution of the increments. For example, in a multi-period model, the final year indicates the time duration modelled. The increments may be in weeks, months or years. Model domain parameters may also represent base line properties. This involves assigning certain model parameters fixed values. This is often done to enable comparison. Model domain parameters can potentially have significant impacts on the model outcomes, yet any uncertainty associated with their setting is often not addressed. The way model domain parameters are fixed determines to what level of detail a model explores a network and what the boundaries to that network are. In picking the parameters, the modeller is trading off between reducing computational complexity while attempting to adequately represent the network. While some values capture the network better than others, model domain parameters, like decision variables, again have no "true" value (with the possible exception of an infinitely detailed model resolution and a model domain set as infinitely large.)

Mathematical models also include a variety of other quantities, such as defined constants, index variables and model outcomes, but these do not have uncertainty associated with them. *Defined constants* cannot be uncertain by their very definition. While the value of the element they represent may well be uncertain, *index variables*, i.e. numbers that identify members of a set, cannot themselves be seen as uncertain. An overview of model parameter uncertainties and examples of these are given in Table 6-1.

6.2.3 Uncertainty in Model Form

According to Morgan and Henrion (1990) model form uncertainty refers to doubts about the adequate representation of the system and encompasses both what is included (system boundary) and how it is captured (mathematical expression). This definition is extended in this thesis to differentiate between model form uncertainty that originates from *mathematical expression*, *system uncertainty* which refers to network structure and performance indicators, and *future uncertainty*, i.e. uncertainty concerning the possible future realisations of the world.

Uncertainty in *mathematical expression* is often caused by lack of knowledge, disagreements among experts or by the subjective judgement used when choosing how to best represent reality or quantify decision-maker objectives and preferences. This can be a significant issue in industrial network analysis, on the one hand due to that fact that industrial networks are large complex structures and how to relate network structure and behaviour to performance. Model form uncertainty in industrial network analysis is caused by questions about what aspects of the network to include (i.e. where to draw the system boundary), to what level of detail the network should be captured and how the proposed sustainable industrial development strategies are incorporated. For a model, these questions raise concerns about the (form of) equations to use to represent the network. For instance, does a linear relationship exist between facility capacity and cost, or are the economies of scales significant? While uncertainties with regards to empirical quantities are well characterised and a number of approaches have been developed to handle them, model form uncertainties are harder to grasp and more difficult to assess. Relatively little research exists in this area, however, model form uncertainty is often more important and more likely to have a substantial effect on the results of the analysis (Morgan and Henrion, 1990). A simple model can have little parameter uncertainty, but it may have significant model form uncertainty. Conversely, a large and complex model may have less uncertainty about the model form, but will have many more input quantities and therefore a higher degree of uncertainty about the model parameters.

Table 6-1 Examples of the different types of uncertainty found in industrial network analysis

TYPE OF UNCERTAINTY		EXAMPLES
Empirical parameter	Random error and statistical variation	Technology efficiency, heating value of fuel
	System error and subjective judgement	Using efficiency data for Facility A to estimate efficiency of facility B
	Linguistic imprecision	“higher costs”, “long distances”
	Variability	Yearly biomass yield, material release from use phase
	Inherent randomness and unpredictability	Yearly market demand for product
	Disagreement	“Density of material is x kg/m^3” (Source A). “Density of material is ykg/m^3” (Source B)
	Approximation	Using of average biomass yield for yearly model interval, instead of detailed data available for monthly interval.
Model parameter	Value parameters	Discount factor in economic indicators (e.g. net present value)
	Model domain parameters	Model time frame, time increment
	Index variables	η_i where index variable is i = 1,2…n (*uncertainty does not apply*)
	Defined constants	Gravitational acceleration 9.81m/s^2 (*uncertainty does not apply*)
Model form	Mathematical expression	Indicator equations, e.g. network profitability (linear or exponential), System equations, e.g. use of process model or aggregate function to represent operation at facility
	System uncertainty	Whether to include facility X
	Future uncertainty	Future state of the world, e.g. ‘renewables will be adopted’, ‘fossil fuels continue to dominate’

System uncertainty refers to uncertainty about *what* should be explicitly included in the model, such as what facilities are included, are information flows and feedbacks to be explicitly considered, what indicators are included, what policies are applied and what type of strategy explored and how is the network linked. These are not uncertainties per se, but rather value judgements about what is relevant to the analysis. However, the problem is that what may be deemed unimportant by a decision-maker may turn out to have a significant influence when explicitly considered. For instance, it may be assumed on the basis of preliminary analysis that the integration of a particular waste stream will provide overall benefit, when this in fact may be more damaging overall than if it were disposed. The same may be true for different indicators. The same choice may suddenly be deemed more attractive when different indicators are included.

Future uncertainty refers to a lack of knowledge about future realisations of the world. While the current policies, prices, nodal performance, network structure and decision-maker priorities may be known, how these aspects evolve my not be certain. While there is generally a desire to maximise strategic advantage, which encourages early investment, future uncertainty raises the fear of sunk costs that cannot be fully recovered, which encourages a delay of the investment until the uncertainties are resolved (Bjornstad and McKee, 2006). Capturing future uncertainty can provide valuable insight how reliably a particular industrial network development pathway is, in other words if the performance of a network structure or performance change.

6.3 CAPTURING AND PROPAGATING UNCERTAINTY IN INDUSTRIAL NETWORK ANALYSIS MODELS

Having discussed the types of uncertainty that may be encountered in industrial network analysis, this section now describes what specific uncertainty analysis approaches are deemed suitable to handle the different uncertainty types discussed in 6.2. The approaches are described and it is elaborated why these are seen as suitable for to handle the specific types of uncertainty.

6.3.1 Probability Distributions for Empirical Parameter Uncertainty

Probability distributions for all uncertain input parameters have to be fitted to available data. A number of possible distributions exist which can be fitted to the available data. However if the data is insufficient to allow a fit, distribution shape parameters or upper and lower limits can be estimated based on the perceived quality of data (“very uncertain”, “low uncertainty”) (Hedbrant and Sörme, 2001).

In order to identify the network development pathway that is best positioned in the face of the possible realisations of the world the uncertainties have to be explicitly and simultaneously considered during the optimisation. This creates a number of challenges for industrial network modelling:

- Deterministic optimisation models of the industrial network may require structural modification, i.e. changes to the coding, to incorporate multi-stage uncertainty.
- The size of the model grows with the number of uncertain empirical parameters.

Due to the curse of dimensionality and increase in model size results in an exponential rise in computational effort. Furthermore, the expression of the probability distributions can give rise to complicated mathematical functions that require sophisticated techniques to solve, such as the L-shaped method and regularised and nested decomposition methods (Birge and Louveaux, 1997). To control the mathematical complexity of the industrial network models, a conceptually simpler form of stochastic programming will be used in this thesis: The model will be split into a discrete number of possible states of the world, each with a specific probability of occurring. This explicit capture of the possible states is also known as the extensive form of the stochastic program (Birge and Louveaux, 1997).

However, the model size grows rapidly with each additional uncertain parameter thus included. Suppose product demand can take on values D_1, D_2 or D_3, each with a probability of occurrence of P_1, P_2 and $P_{3.}$ The model will triple in size. This is because the stochastic model bases the optimal outcome on the trade-off between the state of the network where D_1 occurs ($S_1(D_1)$), the state where D_2 occurs ($S_2(D_2)$), and the state where D_3 occurs ($S_3(D_3)$),. The stochastic model therefore hedges against three possible scenarios of the network, all of which have to be considered simultaneously. To include another uncertain parameter, such as the growth of demand, represented by G_1, G_2, G_3, would increase the size of the model exponentially because then all combinations would have to be considered: $S_1(G_1,D_1)$, $S_2(G_2,D_1)$, $S_3(G_3,D_1$, $S_4(G_2,D_1)$, $S_5(G_2,D_2)$ and so on. Most of the literature therefore only considers one or two uncertain parameters. In the case of SCM this is primarily demand uncertainty (e.g. Gupta and Maranas (2003), Goyal and Ierapetritou (2005) and Gnoni et al. (2003a)). The fact that the full range of uncertainty is not explored in SCM models is pointed out as a weakness by Shah (2005). For large uncertainties, the computational requirements may still be too heavy a price to pay for the additional assurance obtained, and in some cases, this is better obtained by use of a weighted objective function, based on a small number of postulated scenarios (Grossmann and Sargent, 1978; Sargent, 2005). For this reason, a novel approach is adopted in this thesis: Rather than ignoring all uncertain empirical parameters but a few, parameters will be grouped into a “best”, “worst” and “expected” scenario, where each scenario is associated with a specific probability of occurring. The assignment of probabilities to the “best”, “worst” and “expected” scenarios will have significant uncertainty associated with it, as the expectation of these scenarios occurring will be somewhat arbitrary. Consequently, these probabilities will be varied in a sensitivity analysis to determine how strongly the results are affected, and how reliable the results therefore are. The best and worst values are based on the highest and lowest values that a parameter may adopt. Whether “best” corresponds to the highest value or the lowest depends on the context, e.g. a “best” may be the lowest possible cost, but the highest possible efficiency. If no clear distinction can be made about whether “best” is the highest or lowest setting of a parameter, then the highest value is chosen, and vice versa.

The problem with this approach is that the probabilities of the chosen scenarios have to be estimated and do not consider the probability distributions of the individual uncertain empirical parameters. The scenario probabilities are therefore themselves uncertain. They would have to be treated as uncertain model parameters and subjected to uncertainty analysis. However, it can be argued that the likelihood of the best case occurring refers to the chance of that particular combination of parameters occurring. The alternative would be to limit the stochastic optimisation to a few uncertain parameters, but in this case the choice of which parameters would be included and which rejected would be contentious, unless some form of importance testing shows that only a very few parameters have a significant impact and all other can be safely ignored. The other problem with restricting the stochastic optimisation to a few parameters, (or alternatively taking each significant uncertain parameter and doing a separate stochastic optimisation) would also cause doubt about the quality of the results is that the ability to hedge would be reduced.

6.3.2 Interval Testing for Handling Model Parameter Uncertainties

Interval testing is suitable to capture model form uncertainty in both optimisation models. This approach tests reliability in the models by assessing if, or to what extent, the model response changes significantly in relation to changes in model parameters. The uncertain parameter is described and bounded by the minimum and maximum value and the response of the network is sampled for a limited set of points.

6.3.3 Sensitivity Testing for Handling Model Form Uncertainty: Mathematical Expression

The effect of model form uncertainty in industrial network analysis can be assessed in two ways: 1) In some cases the uncertainty in model form can be converted into parameter uncertainty. It has been recommended that this can then be handled by *interval analysis* (Basson, 2004). For instance, if there is uncertainty regarding a dose-response function, then that can be expressed as uncertainty regarding the threshold and exponent parameters. In some cases a “meta-model” can be created that includes different model forms in parallel and that are called according to different index parameters. 2) If the conversion of model form into model parameter uncertainty is not possible, the influence of model form uncertainty can be checked by another form of sensitivity analysis. In this case the sensitivity of model outcomes to the use of different model structures can be compared.

6.3.4 Scenario Analysis for Handling Model Form Uncertainty: Future and System Uncertainty

Uncertainty concerning network structure or future developments that are seen as likely can be incorporated in models by means of scenario analysis. As scenarios represent fundamentally different network states and developments, they have to be identified and considered very early on in industrial network analysis. Scenario generation is therefore included as a distinct step in the industrial network analysis framework. Scenario generation was discussed in detail in the previous chapter.

6.3.5 Considerations for Handling Valuation Uncertainties

For disagreements in choice of objectives, indicators, functions and differences in preference valuation, i.e. valuation uncertainties which may occur during industrial network analysis, it would be preferable for stakeholder or final decision-makers to discuss these and attempt to reach a consensus, rather than accounting for these uncertainties mathematically. The debate would require the detailed elicitation and justification of view points and the uncertainty could thus be reduced, resulting in a model that addresses the (now well defined) problem better and consequently yields more useful results.

6.4 REDUCING UNCERTAINTY

As the discussion so far has highlighted, the degree of uncertainty that enters not only the network model, but also the preceding problem structuring may be extensive. Even if it would be possible to account for every single uncertainty, the time and effort required to gather better quality data, reconcile stakeholder views etc would be too large to be practical in many cases. It is therefore attractive, if not necessary, to reduce the uncertainty that has to be engaged with. The following criteria can give some initial guidance on how this should be approached (Morgan and Henrion, 1990):

- *Uncertainty about model form*: It is of no use performing detailed assessments on the impact of model parameter uncertainties if the model structure and relationships are not well known, in other words if there are doubts with regards to the form of the network and the equations used to describe it. This may be the case with highly abstracted network models or when exploring the use of new technologies and new network designs.
- *Requirements of the analysis*: If the analysis is meant to deliver first pass, qualitative insights into network performance, then detailed consideration of uncertainty may not be necessary. For

determination of a preferred network development pathway, it is more important to check under which conditions the identified network states or strategies are valid, thereby reducing the extent of uncertainty analysis necessary.

- *Resource availability*: Time, money and human and technical resources may limit the degree to which uncertainty can be addressed.

The level of detail of the uncertainty analysis is thus not only a function of the industrial network, but is also dependent on the purpose of the analysis, and should be based on prioritisation effort. In some cases, however, uncertainties may be too great to be effectively managed by (quantitative) techniques, specifically where the analysis enters the realm of ignorance (Funtowicz and Ravetz, 1990). In this case even increased effort will achieve little reduction in uncertainty.

6.4.1 Screening on the Basis of Uncertainty Importance

It may only be worthwhile to expend the extra effort of reducing the degree of uncertainty if it has been shown that added data, more detailed uncertainty assessment and model refinement will make a significant difference. In other words, key issues have to be identified where the uncertainty is significant. Heijungs (1996b) distinguishes between uncertainties that are a key issue because they make a significant contribution, i.e. the network is sensitive to changes in them and those that become key issues due to the magnitude of uncertainty, indicated for instance by the possible range or the standard deviation of a parameter. With a large number of uncertainties, the question is however not confined to how strongly one uncertainty affects the network analysis outcomes, but also how multiple uncertainties interact. These methods are only applicable to screening model and empirical parameters.

In the case of optimisation a change in parameter may result in a change of several of the decision variables, such as the material flows and allocation. In terms of determining preferred network development pathways via optimisation, it is not only valuable to know to what extent economic/environmental/social performance is affected, but also if a change in certain parameters, or even a number of parameters, will result in a completely different pathway. This will be an indication that whatever network structure is recommended by the stochastic optimisation, which hedges for the different possible realisations of uncertainty, will still be a risky prospect.

As the effect of uncertainty is analysed and parameters with significant impact and those with little effect are identified, uncertainty will be reduced with the number of iterations performed for the uncertainty analysis.

6.4.1.1 *Parameter variation (interval analysis)*

The simplest approach is a sequential varying of the uncertain parameters to their best and worst values to determine the effect, if any, this has on model outcome. The drawback of this approach is that it is not able to assess parameter interaction.

6.4.1.2 *Symbolic sensitivity analysis*

This approach determines sensitivity, i.e. the rate of change of the objective, or model outcome with respect to changes in input parameters. This approach is particularly attractive for optimisation problems as it does not require repeated model runs. In other words, the sensitivity information is derived from the equations directly. The approach is applied in the following manner: For an objective of the form

$$f(x, y, z) = ax + by + cz \qquad 6\text{-}1$$

With constraints

$$mx + ny = d \qquad 6\text{-}2$$

$$ox + pz = e \qquad 6\text{-}3$$

A new objective function L can then be created by substituting the constraints into the original objective function *f(x,y,z).*

$$L(x, y, z) = (ax + by + cz) + \lambda_1(mx + ny - d) + \lambda_2(ox + py - e) \qquad 6\text{-}4$$

Where λ_1 and λ_2 are Lagrangian transforms. (If the model includes inequality constraints, then Karush-Kuhn-Tucker KKT transforms have to be used.) The sensitivity of this equation with regards to changes in each of the variables *x, y, z* can be determined by taking the derivatives.

$$\frac{dL}{dx} = 0 \quad \rightarrow \quad f_1(a, b, c) = 0 \qquad 6\text{-}5$$

$$\frac{dL}{dy} = 0 \quad \rightarrow \quad f_2(a, b, c) = 0 \qquad 6\text{-}6$$

$$\frac{dL}{dz} = 0 \quad \rightarrow \quad f_3(a, b, c) = 0 \qquad 6\text{-}7$$

Equations 6-5 to 6-7 can be substituted back into the original objective function. The objective will then be in terms of all the parameters *a,b,c, m, n, d, o, p, e* and the effect of uncertainty in these parameters can be explored symbolically. However, for larger and/or complex problems special software has to be used to solve the equations[23].

6.4.1.3 Factorial design

A much more efficient method is factorial design or fractional factorial design (Box et al., 1978). “Factor” refers to the uncertain parameters. Factorial design involves taking the extreme (minimum and maximum) values[24] that each uncertain parameter may adopt and varying them against each other until all possible combinations have been explored. Fractional factorial design has been used extensively in PSE to determine parameters with the biggest influence on model outcomes. In SCM, the approach is less commonly employed. Here it is commonly used to determine the most influential parameters and use these to create robust designs or response surfaces that only consider the important parameters.

Through interrogating the results of each run, it can be determined which uncertain parameters dominate and where interactions exist. However, for n uncertain parameters, 2^n runs will have to be performed. The computational effort therefore increases rapidly. However, depending on the nature of the problem, the number of runs necessary to get meaningful insight into the contribution and correlation between uncertain parameters can be reduced, thereby giving rise to a *fractional* factorial design (FFD). For example, if the problem is linear in terms of its uncertain parameters (e.g. ax^2+by^2 is linear in terms of the parameters a and b) then the Plankett-Burman (PB) approach can be used (Plackett and Burman, 1946). This approached is used in this thesis.

6.4.1.4 Marginal sensitivity information

Some preliminary idea of uncertainty importance in optimisation models can also be inferred from the algorithm-based, or marginal, sensitivity data. Marginal values, such as *shadow prices* and *reduced costs,* are based on the dual, which is a function generated during both linear and nonlinear optimisation. Subsequently this information can be retrieved from the output generated by many optimisation software packages. These give an indication of how much the objective value is likely to change if the right hand sides of model constraints are relaxed each by one unit and by how much an objective function coefficient must be changed before the associated variable becomes part of the optimal solution, respectively. This has been mentioned in a paper by (Azapagic and Clift, 1999b) as a possible means to determine the effect of uncertainty on Pareto optimal solutions in a process system. However, algorithm-based sensitivity information has to be interpreted with caution, especially with integer models where the information may only apply over very limited ranges. Marginal sensitivity data has two further disadvantages: 1) it does not

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[23] Personal communication with A. Chakraborty, March 2007.

[24] Although 3 factor (or greater) designs are possible if in addition to the minimum and maximum possible values, the average values of the uncertain parameter, or factor, are to be explored.

give insight into the network response to input changes over the entire uncertainty range and 2) it does not take uncertainty interaction into account. Consequently this approach is not used here.

6.4.1.5 Determining optimal model complexity

Another possible method of determining the influence of empirical parameter uncertainty as well as model form has been suggested by Subramanyan and Diwekar (2007). In their paper the authors attempt to determine a sufficient level of model complexity and detail by comparing the results obtained from simple models (which contain more uncertainty) and more detailed models. The latter are more accurate, but increase the computational burden. By comparing the deterministic results with stochastic results in each case (simple and detailed), and results from the simple model and the detailed model, they showed that little difference between the deterministic and stochastic results in the detailed model indicates that the model has sufficient accuracy and complexity to be used to represent a process system.

However, for this approach to bring additional benefit, more detailed information needs to be available. This information also needs to be more accurate - which is not necessarily a given just because model detail is increased - else model results would still be uncertain. This approach therefore has limited applicability to industrial system analysis, for the following reasons: The authors are able to validate the more detailed model through comparison of model results with experimental results, which would also not be possible when applied to problems at the scale of industrial networks, for the reasons discussed in section 5.5. Consequently it may better to adopt the greatest level of detail that fits with the requirements of the analysis: For the identification of trends, simple models suffice, if accuracy is important, the additional effort of creating and running more detailed models becomes worthwhile.

However, one valuable thought here is that the discrepancies between deterministic and stochastic model outcomes provide an indication of the extent that uncertainty affects model results. This can be used to assess the reliability of outcomes in industrial network analysis.

6.5 UNCERTAINTY ANALYSIS FRAMEWORK FOR INDUSTRIAL NETWORK ANALYSIS

The preceding sections have provided an overview of the types of uncertainties expected to enter industrial network analysis and what approaches are available and suitable to handle these uncertainties. This section revisits the industrial network analysis methodology of Chapter 5 and discusses where different uncertainties enter and how these uncertainties are may be addressed. Furthermore, a framework is provided describing how the individual quantitative approaches for handling the different types of uncertainties are combined to allow simultaneous assessment of all uncertainties that are explicitly captured in the industrial network model.

6.5.1 Uncertainty in Problem Structuring

The problem structuring aspects introduce numerous uncertainties in each of its steps. A detailed overview of the sources of uncertainty in the problem structuring and types of uncertainties that can be encountered during these stages are given in detail in Table 6-2, together with an explanation of what these uncertainties are and which of the approaches discussed in 6.3, if any, are recommended to address the uncertainties. Many of these steps require decision-makers and stakeholders to make choices based on their preferences and are thus valuation uncertainties. The initial problem definition may already introduce valuation uncertainty in that it may be contentious what the sustainable development issues are in the given context, which are important and how they are best addressed (Table 6-2, **1**). As the problem definition influences all subsequent analysis steps, such as choice of network boundary, objectives and indicators, it is vitally important that disagreements at this stage are best resolved through stakeholder discussion, as mentioned in section 6.3.5. Even if the problem is clearly defined, capturing the network boundary and defining network structure will be subject to technical uncertainties. While the choice of network representation is subject to subjective judgment, the uncertainties will affect the representation of the model, rather than how that model is evaluated (Table 6-2, **2**). However, the choice of stakeholder is also based on subjective judgement when it is decided whose views and inputs are important and relevant and should therefore be involved. The network boundary provides an indication of which stakeholders are affected and have to be involved in the structuring process. In turn, the stakeholders influence the various choices and definitions through their different perspectives and priorities. The views of stakeholders not directly involved in the industrial analysis process should therefore be determined and considered through role play to see if further perspectives provide new uncover additional insights or issues that should be considered (Table 6-2, **3**).

Finally, objectives and indicators have to be defined in a manner that the performance of the network are adequately captured (Table 6-2, **4&5**). The choice introduces valuation model form uncertainty, whereas the formulation of the indicator equations to measure performance will introduce technical model form, model parameter and empirical parameter uncertainties.

Table 6-2 Sources, types and approaches to uncertainty in problem structuring

SOURCE OF UNCERTAINTY	TYPES OF UNCERTAINTY	EXPLANATION	APPROACH
1. Problem definition	Valuation model form uncertainty	Some subjective interpretation of the problem will be required during the application of the methodology to specific cases. The uncertainty about the exact meaning of sustainable development will influence all subsequent analysis steps	Definition of problem should be discussed with stakeholders as part of the exercise to determine which objectives and indicators best assess the network's performance with respect to sustainable development.
2. Definition of network boundary and network structure		Influences the geographical and temporal scope of the model and thus the entities and dynamic developments that will be included.	Should be resolved by stakeholders, unless good reasons exist for evaluating different boundaries.
	- Technical model form uncertainty (system, future) [25]		- Evaluated through different scenarios
	- Technical model parameter uncertainty		- Uncertainty in the model domain parameters can be evaluated through sensitivity testing.
3. Identification of stakeholders	Valuation model form uncertainty	In large industrial networks consisting of a diverse range of companies, agencies and other agents, it may be difficult to determine all relevant stakeholders. Stakeholders external to the network may also hold an interest.	Uncertainty in the choice of stakeholders to include can be mitigated by involving as many stakeholders as possible, or role playing the ones that for practical reasons cannot be directly involved to still get an indication of their perspective (Basson, 2004).
4. Choice of objectives	Valuation model form uncertainty	Stakeholders may differ in their views on which objectives best represent performance with respect to sustainable development.	Should be resolved by stakeholders, unless good reasons exist for evaluating different objectives or criteria. Can otherwise be evaluated through sensitivity testing.
5. Choice of indicators	- Valuation model form uncertainty	- Stakeholders may differ in their views on which indicators best measure performance of the chosen objectives.	Should be resolved by stakeholders, unless good reasons exist for evaluating different indicators. Can otherwise be evaluated through sensitivity testing.
	- Technical model form uncertainty	- Uncertainty about mathematical description of how network performance correlates to network activity and structure	

6.5.2 Managing Uncertainty during Quantitative Analysis

The sources and types of uncertainty in the quantitative analysis are given in Table 6-3, together with a detailed explanation of what these uncertainties are, and what approaches, if any, are recommended to

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[25] While these choices are subject to subjective judgment, the uncertainties will affect the representation of the model, rather than how that model is evaluated.

address the uncertainties. Figure 6-1 graphically illustrates how the uncertainty analysis methodology affects the network analysis part of the industrial network analysis.

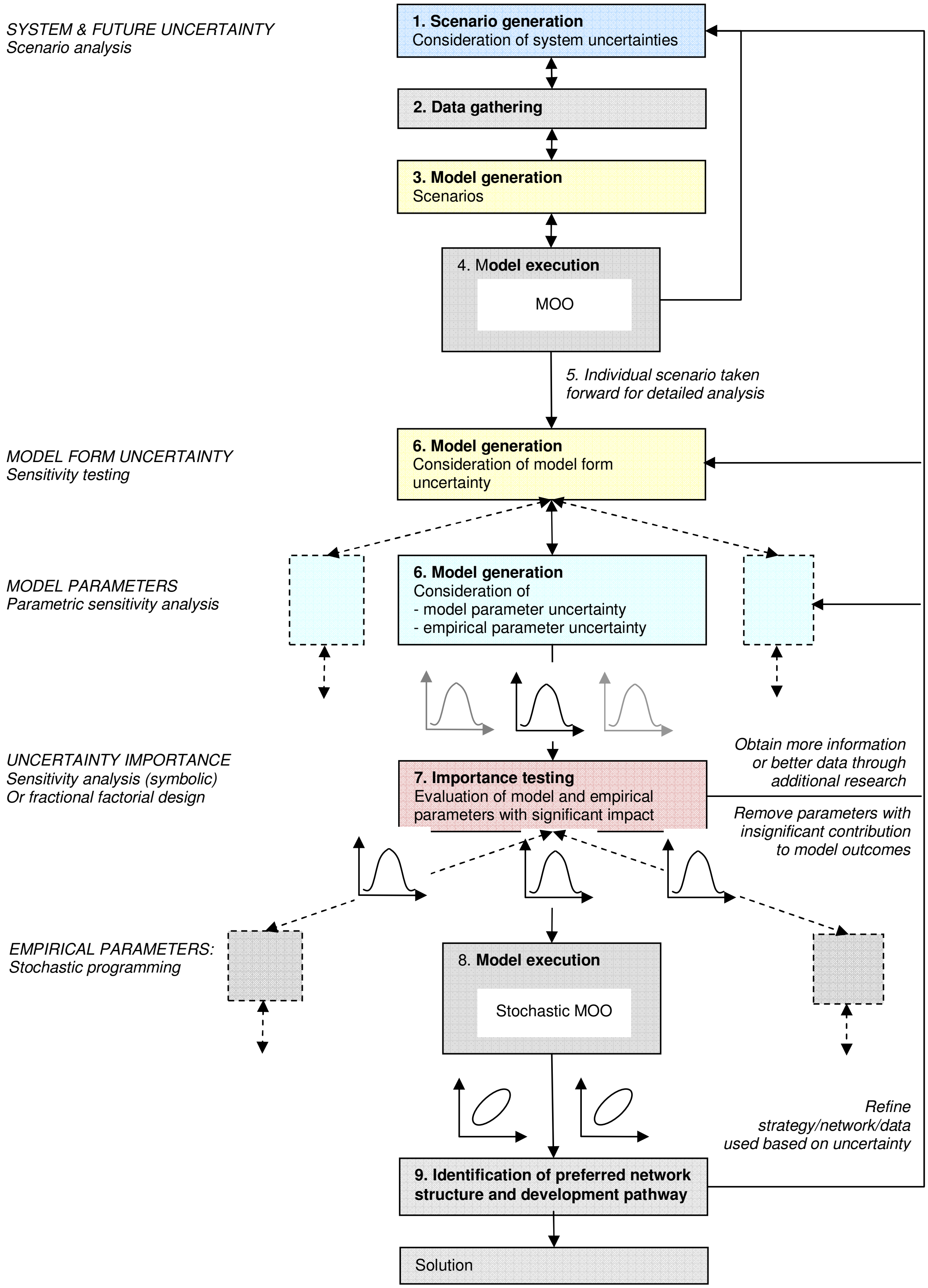

Figure 6-1 Methodology for incorporating uncertainty in modelling

Where the problem structuring was dominated by valuation uncertainties, the quantitative analysis of the industrial network deals principally with technical uncertainties, as the network has to be characterised in its structure and technical, environmental, economic and social performance.

The quantitative analysis process begins with scenario creation. The creation of scenarios suffers from similar uncertainties as the network boundary definition (Table 6-3, Figure 6-1, **1**). Here different strategies, network structures and future developments have to be defined and each will affect technical, but also valuation model form if for instance the effect of indicator choice is to be evaluated. The defined scenarios subsequently have to be evaluated to determine which ones are to be taken forward to quantitative analysis. While the choice of scenarios is based on subjective judgment, the uncertainties will affect the representation of the model, rather than how that model is evaluated.

After the set of relevant scenarios has been identified, the necessary data for the model development has to be gathered. The data gathering does not per se introduce uncertainties, except where data is overlooked. However, this falls into the realm of ignorance and cannot be accounted for (Table 6-3, Figure 6-1, **2**). It is here that uncertainties, especially empirical uncertainties, will have to be noted and characterised. It is important during this stage to take note of the ranges of parameter values reported, the different equations or model cited and their transferability to the given context and disagreement among sources.

The next step is the model generation for the scenarios and executing these models (Table 6-3, Figure 6-1, **3&4**). For the uncertainty analysis, it is proposed in this thesis to separate the quantitative analysis into two steps: the first includes the exploration of the scenarios (Table 6-3, Figure 6-1, **3-5**); the second step will use *one* scenario and evaluate the affect of uncertainty in detail (Table 6-3, Figure 6-1, **6-9**).

It is recommended that the scenarios are evaluated through single objective optimisation and potentially also by MOO *without* a detailed consideration of uncertainty in the underlying equations used or model and empirical parameters, for the following reasons:

- Future and system uncertainty is in most instances expected to dominate uncertainty in how network performance is described and the numbers used to populate the model.
- Scenario analysis is intended to provide information on the effect that future and system uncertainties have. An indication of trends would be sufficient in this case and this can be delivered without detailed insight into uncertainties.
- A full description of the effect of uncertainty and representation of the possible ranges of network performance for each scenario would provide a potentially overwhelming amount of information on network performance under uncertainty. This wealth of information would likely confuse a decision-maker and decrease the decision-maker’s ability to determine of preferred network structures and development pathways.

- A detailed uncertainty analysis for each scenario chosen would become very time intensive, due to the need to collect information on the underlying uncertainties. This, in light of the above points, appears to be an additional effort that would not be justified by the additional insight provided.

Based on the insights obtained form running the individual scenarios *a single scenario should be identified* that is taken forward to a detailed uncertainty analysis (Table 6-3, Figure 6-1, **5.**). This can be one of the already generated scenarios, or a new one can be constructed based on the insights of the analysis of the individual scenarios. Features identified as either being very likely, as being able to improve performance in one or more objectives, and/or having a large impact on analysis outcomes can be combined into a single scenario. Similarly to the initial choice regarding which scenarios are to be considered quantitatively (step **1**.) there will be some uncertainty as to whether the chosen scenario adequately captures the situation. However, the scenario analysis should have provided some reassurance that important future or system analysis aspects have been identified.

For the single scenario taken forward, uncertainties in mathematical expression and model and empirical parameters are considered in detail (Table 6-3, Figure 6-1, **6.**). A degree of valuation model form uncertainty at this stage is also introduced by the choice of MOO method used. For instance, if using an *a posteriori* method, where the entire possible performance of the network is evaluated before making a choice of preferred solution, the choice of preferred network development pathways may differ from the preferred solution if an a priori method were used, where priorities are decided before the possible network performance is known. In the case of MIP and NLP optimisation problems, there may be uncertainty in whether a global solution has been identified. There is no way this can be definitively tested, however, through good structuring of the model and through the use of sophisticated search methods, such as tabu search which enhances the performance of a local search method (Glover, 1989, 1990), the chance of finding close to global or globally optimal solutions can be increased.

Table 6-3 Sources, types and approaches to uncertainty in quantitative industrial network analysis

SOURCE OF UNCERTAINTY	TYPES OF UNCERTAINTY	EXPLANATION	APPROACH
1. Scenario generation	- Technical model form uncertainty (system, future) [5]	- Uncertainty about the exact form of the models that should represent the scenarios, and which future developments may occur. - Uncertainty about which scenarios are important	The number and form of scenarios needs to be resolved by stakeholders until all or the most important or interesting strategies, network structures or future developments are being explored.
2. Data gathering	- Empirical parameter uncertainty	Data gathering process may introduce uncertainty, such as oversight of important information or disagreement between sources	This uncertainty will only be expressed during the **model generation** stage.

Table 6-3 contd. Sources, types and approaches to uncertainty in quantitative industrial network analysis

SOURCE OF UNCERTAINTY	TYPES OF UNCERTAINTY	EXPLANATION	APPROACH
3. Scenario model generation	Same as in step 6.	Same as in step 6.	Due to the difference between scenarios, which are assumed to dominate uncertainty in mathematical expression and parameter uncertainties, these **uncertainties are not considered at this stage**
4. Scenario model execution	N/A		
5. Choice of scenario to take forward		Uncertainty about the exact form and content of the scenario taken forward	Scenario analysis should provide reassurance that important features are included in the scenario taken forward.
6. Model generation	- Technical model form uncertainty	- Uncertainty about accuracy of mathematical representation of the industrial network and its performance	- Sensitivity testing
	- Valuation model form uncertainty	- Uncertainty about allocation of impacts	- Scenario analysis with different impact allocation
	- Technical model parameter uncertainty	- Uncertainty in the values used.	- Interval analysis
	- Empirical uncertainty	- Uncertainty in the values used.	- Stochastic optimisation
- Multiobjective optimisation	- Valuation model form uncertainty	- Different Pareto optimal solution generating methods may identify different outcomes.	- Use of *a posteriori* methods (used to best effect in interactive methods) will generate entire solution space, thereby reducing the uncertainty. The effort of regenerating result with a different method is likely to involve more effort than benefit
		- For nonlinear problem and mixed integer problems, there may be issues with identifying a global optimum.	- Use of more sophisticated search methods to identify global optimum.
7. Importance testing	Valuation model form uncertainty	Different approaches may identify different parameters as important.	Use of more thorough method (e.g. fractional factorial design)
8. Model execution	N/A		
9. Identification of preferred network development pathway	N/A		

For the simultaneous consideration of uncertainty in mathematical expression, model parameters and empirical parameters a nested approach is recommended. This nested approach to the uncertainty assessment is based on a framework by Notten (2001). Within the chosen scenario different possible mathematical expressions may be identified that describe certain aspects of the network. Next, within each of these models with different mathematical expressions, the model parameter ranges and increments over which they are to be tested are determined. Finally, for each permutation of the uncertain model parameters the empirical parameter uncertainties are first defined and then propagated through the model via stochastic MOO.

Depending on the method used of those suggested in section 6.4.1, importance testing may highlight different parameters as being important (Table 6-3, Figure 6-1, **7**). For instance, interval analysis does not take interactions into account in the way the fractional factorial design does. By contrast, FFD may assign higher importance to parameters that significantly affect several other parameters. Methods such as FFD and symbolic sensitivity analysis may therefore be preferable. Consequently FFD is applied in the case study in Chapter 7. This is compared to interval analysis, which is applied in Chapter 8.

6.6 CONCLUSIONS

In this chapter we have covered, both generally and in the case of industrial network analysis in particular

- the types of uncertainty that may affect analysis,
- how these uncertainties can be captured and expressed for mainly quantitative, but also qualitative analysis (in the case of value judgements) and
- how to streamline analysis by focusing on the key uncertainties.

The industrial network and the sustainable development context, as well as their associated complexity, discussed in Chapters 2 and 3, give rise to significant uncertainties during all stages of the industrial network analysis. The goal of the uncertainty assessment described in this chapter is to increase the usefulness of data to a decision-maker. Quantifying all the uncertainties in an industrial network model can be a daunting task for a modeller and a decision-maker can be confused by the amount of results generated. Uncertainty assessment should therefore be as extensive as the available resources will allow, but focus on increasing confidence in model structure and parameters, as well as the outcomes by forcing the modeller to engage with the quality of the data and the reliability of the underlying assumptions. This requires a trade-off between model detail and the extent of the uncertainty analysis based on the resources available. In section 6.4 approaches were therefore recommended that allow prioritisation and thereby screening of uncertainties. Even if uncertainty cannot be reduced and any decision retains a degree of risk, the uncertainty analysis has the benefit that it forces the decision-makers to engage in more detail with the network analysis and to be more critical of the underlying assumptions, choices and values. However, even using approximate data is often more effective than abandoning the analysis effort (Shapiro, 2001).

The key contributions of this chapter are:

- The identification of where in industrial network analysis what type of uncertainties affect industrial network analysis.
- How uncertainty analysis approaches identified in Chapter 4 can be used to address these uncertainties during problem structuring (particularly valuation uncertainty), and to propagate these types of uncertainties through the MOO models.
- The combination of the chosen uncertainty analysis approaches in a framework, which was adapted for industrial network analysis from work done by Notten (2001), to allow a comprehensive consideration of the effect of uncertainty on a proposed network structure and development pathway.

In the next two chapters the industrial network analysis is applied to a wood products case study and a biomass to energy case study respectively. The main difference between these case studies is that the former explores the implementation of sustainable development strategies in an existing network, whereas the second case study explores network design, i.e. network formation from new and existing infrastructure. Both case studies include a detailed assessment of uncertainty to assess the robustness of the proposed network development pathways.

7

CASE STUDY 1: RESOURCE EFFICIENCY IN THE WOOD PROCESSING INDUSTRY

7.1 INTRODUCTION

In this first case study, industrial network analysis is used to identify means of promoting sustainable development in an *existing network*. In such a network, the existing locations, capacities and technologies of the facilities will constrain the extent to which interventions for sustainable development can be implemented.

The case study focuses on the wood processing industry in the Sydney Metropolitan Area (SMA) of Australia. In this case study the effect of increased integration on overall economic and environmental performance, i.e. better resource utilisation of material flows between industrial units in a wood product network is explored. This increased integration is meant to address several of the sustainable development issues identified in Chapter 2, namely waste disposal and the possible overuse of renewable resources. The integration consists of linking two currently distinct supply chains through additional infrastructure and new technology, a key and unique feature of this case study. The two supply chains each deliver a wooden product: one chain supplies pallets, which are used for transport, the other chain supplies particleboard, which is used in the manufacture of furniture, such as kitchen cabinets. Discarded pallets form part of the commercial and industrial (C&I) waste stream, whereas old particleboard primarily enters construction and demolition (C&D) waste. This linear use of wood, from plantation forests which have replaced native habitat, to landfill, represents a waste of wood resources which could be recycled for further use, either directly or indirectly.

The consideration of the effects of linking two or more supply chains through reintegration is a departure from the more economically focused supply chain view, or the single product focused view of most life-cycle analysis. In these cases, opportunities for sustainable development or economic advantage tend to be analysed with a focus on the implications only for a specific process, product or firm. This research, and more specifically this case study attempt to show the implications of material loop closure on the wider system, for instance how other supply chains are affected by the decision to recycle.

Furthermore, this case study will illustrate:

- **opportunities for network integration** through infrastructure changes and use of innovative technology. IE is based on the premise that the increased closure of industrial systems, i.e. where material and energy are cycled, provides environmental benefits. This case study applies the industrial network analysis framework to test some of the strategies recommended in Chapter 2, particularly reintegration. Reintegration was discussed as a possible strategy to protect virgin resources, both renewable and non-renewable, as well as to avoid waste generation and strain on the environment's assimilative capacities. Reintegration was chosen as the strategy to explore in this case as it suits the particular needs of the network chosen for the case study. The specifics of the case study and the motivation for reintegration will be explained in further detail in the next section.
- **the extent to which performance is affected through the implementation of a proposed sustainable development strategy** with respect to a set of relevant sustainable development indicators. The effect of the chosen strategy is not only of interest in regards to the effect it has on the environmental performance of the wider network, but also its effects on economic and social performance. It was argued in Chapter 1 that sustainable development does not only require improved environmental performance, but that this has to be weighed against the associated costs, both economic and social.
- **how analysis outcomes are affected when uncertainty in assumptions and data is considered**. The uncertainty analysis is intended to show how robust the performance of the strategy is under different possible states of the world. This is important, especially when dealing with complex structures such as industrial networks where a great amount of data is necessary to describe their performance. Consequently, a significant degree of uncertainty is therefore expected to enter the analysis. Uncertainty analysis is often neglected when evaluating the environmental benefit of decision. The intent here is to show that the additional effort expended provides valuable additional information, and, depending on the outcomes, potentially greater confidence in the proposed development strategy.

Before applying the methodology outlined in Chapters 5 and 6, some background on the case study is given.

7.2 CASE STUDY BACKGROUND: WASTE AVOIDANCE

Australia is covered with 164 million hectares of forest, roughly 20% of its total surface area. In NSW, in excess of 1.25 million hectares of forest are available for timber production. The majority of softwood is plantation grown, whereas the hardwood is predominately eucalyptus species from native forests (Forests NSW, 2006).

Wood waste is defined as "*end-of-life products, failed products, off cuts, shavings and sawdust of all timber products*" and it excludes forest residues, often referred to as primary wood waste, and green or garden waste materials such as branches, bushes and tree stumps (Warnken et al., 2001). Wood waste constitutes a significant portion of waste consigned to landfill in Australia. It is estimated that Sydney alone generated about 335,000 to 350,000 tonnes of wood waste in 2005 (Taylor et al., 2005). In the SMA in 2003, and on a mass basis, roughly 50% of waste sent to landfill was C&I waste, and another 25% is C&D waste, and the remainder being municipal waste (Department of Environment and Conservation NSW, 2004). In fact, timber products constitute about 16% by mass of the C&I waste stream in the Sydney Metropolitan Area (Department of Environment and Conservation NSW, 2004) and 47% of C&D waste (Department of the Environment and Conservation NSW, 2003).

In 2003, the *NSW Waste Avoidance and Resource Recovery Strategy* was released (Resource NSW, 2003). This document set broad targets to reduce waste generation, increase recovery, and reduce toxic substances, litter and illegal dumping. For wood waste, reduction, reuse, direct or closed loop recycling and indirect or open loop recycling and energy generation are identified as the four main processing options identified for end-of-life wooden products (Taylor et al., 2005). However, lack of information on available waste streams, as well as contamination, unidentified or lack of markets, issues with security of supply, legislation and missing infrastructure are cited as the major barrier to increased wood products recycling and reuse.

7.2.1 Particleboard

Particleboard is the dominant panel product in Australia. In 2005/2006 about 1,002,000m^3 of particleboard was manufactured in Australia, of which around one third went into the manufacture of cabinets, another third into furniture, and the remainder into flooring and shop fitting and miscellaneous use (ABARE, 2006; Jaakko Pöyry Consulting, 1999). It is traditionally made from softwoods, but increased quantities of hardwood thinnings and sawmill residues are being used (Margules Poyry Pty Ltd, 1999). Particleboard is produced by coating wood chip with a mixture of thermosetting binder (commonly formaldehyde-based aminoplastic resin) at about 10%w/w on dry wood. It sells at a price of about AU$ 200-300 per cubic metre (Taylor et al., 2005). As cabinets, particleboard has an estimated life of 18-30 years (Jaakko Pöyry Consulting, 1999).

Despite the fact that particleboard production has increased at a rate of 2.3 % annually since 1985 it is predicted that consumption will fall to similar levels to those in the mid-80s by 2040 (Stafford and Neilson, 1996). In other words, per capita consumption is predicted to fall from 41kg in the 5 years from 2000-2005 to 26kg in the 5 years leading up to 2040, which constitutes a demand decrease of roughly 35% (Stafford and Neilson, 1996).

7.2.2 Pallets

Pallets are portable platforms used for storing or transporting cargo, and it is estimated that they remain structurally intact, in the case of hardwood pallets, and hence re-usable, for up to three years (Jaakko Pöyry Consulting, 1999). Hardwood and softwood pallets constituted roughly 18% of domestic hardwood timber product and 7% of softwood timber product in 1999 (Jaakko Pöyry Consulting, 1999). Assuming that these fractions have not changed much in seven years this would amount to over 230,000m^3 in both hardwood and softwood used for pallet manufacture (ABARE, 2006). It is expected that the use of hardwood timber will drop, attributed to increased availability in softwood and regulatory limitations on native forest harvesting. Softwood timber use on the other hand is growing at around 5% per annum from 1985 (ABARE, 2006; Attiwill et al., 2001).

7.3 APPLICATION OF METHODOLOGY

7.3.1 Problem Definition

The problem has already been framed in Chapter 2 for industrial network analysis: Industry operates unsustainably due to the issues of overexploitation of renewables, use of non-renewables or hazardous substances, low efficiency, waste generation and excessive consumption. Chapter 2 provided a general description of issues, and this description serves as a guideline for problem identification in the wood processing industry in the SMA.

The problem in this particular case is the large amount of wood waste being generated and disposed of each year in the SMA. The NSW government desires to find alternatives to landfill for these waste streams. The aim of the industrial network analysis in this case is therefore the reduction of waste. The only means to avoid disposal is to find alternative uses for the wood waste. This has the added benefit that virgin resources can be substituted, reducing the pressure on renewable and/or non-renewable resources. Overall this **problem can also be seen as one of low resource efficiency**. Resource efficiency, in its most general form, refers to the reduction of material input, i.e. resource use, compared to material output, i.e. consumption and eventual disposal. Hanssen (1995) expands on this definition, saying that the aim is to "*reduce the mass flows within the product system, e.g. by making the product more efficient, or by reducing consumption of some raw materials; reduce emission factors or resource consumption factors, or change to other types of emissions or resources, e.g. by reducing emissions and energy consumption per kilogram of product produced; change types of emissions or types of resources used in the system, e.g. by technology changes or by using other types of raw materials.*".

While the aim is to reduce resource use and minimise landfill volume, an exclusive focus on resource efficiency would constitute a narrow view of sustainable industrial development. The major disadvantage is that the concept of resource efficiency 1) does not consider the impacts of material processing, such as energy intensity or emissions, and 2) it does not give an indication of the utility of the products. The aim in this case will therefore be **to identify means to improve the resource efficiency of the wood processing industry in the SMA, while ensuring that other environmental impacts are minimised.**

This problem definition provides the basis for all the subsequent analysis steps, influencing the system boundary definition, the strategy or strategies chosen to address these issues and the indicators chosen to reflect to what extent performance with respect to sustainable development is improved. This step is therefore the most important in industrial network analysis, as the quality of the outcomes depends on the "right" problem being defined.

7.3.2 Definition of System Boundary

In Chapter 5 it was stated that the system boundary should firstly include the life-cycle of affected products to capture how any recommended strategies affect the up- and down-stream processes. Secondly, the system boundary is influenced by the issues that need to be addressed and the strategies to be implemented, i.e. the sources of the issues should be included as well as the structural changes that result form the strategy. Before it can be decided how the existing network should be adapted for the purpose of addressing the issue identified in the problem definition, it is necessary to first look at existing infrastructure.

The case study includes two products, pallets and particleboard, representative of C&I and C&D waste, respectively. Currently these product chains are predominately linear, with most material going directly from forest through to landfill (Figure 7-1). The model developed for this case study covers the life-cycles of the two products, from wood harvesting to processing and manufacture, use to disposal of all waste. For pallets, this includes the delivery of timber from the forests, sawmilling to obtain cut timber, pallet manufacture and use of pallets for product delivery. The particleboard life-cycle also relies on plantation timber as a raw material, but also uses wood chips that are a by-product from sawmilling. These raw materials are chipped, compressed and glued at the particleboard mill. From there the particleboard is sent to a cabinet maker converting the boards into kitchen cabinets and other final products. These are sold to customers, and have a residence time in the economy of 15-30 years, whereafter they are demolished and landfilled.

The only point of connection between the two supply chains which currently exists is the use of chips for particleboard manufacture within the “primary processing” node in Figure 7-1.This current configuration of the network will act as the base case against which to compare the performance of the integrated network.

For the creation of a resource efficient network, opportunities for material *reintegration* have to be identified within the network. Reintegration is therefore the strategy adopted in this particular case study, although as a consequence of the reintegration, virgin raw material will also be substituted. The network boundary needs to be extended to include new technologies that may facilitate reintegration, as well as alternative destinations for any waste material that are not currently being exploited. In the next section it will be demonstrated how this strategy is fitted to the wood products case study.

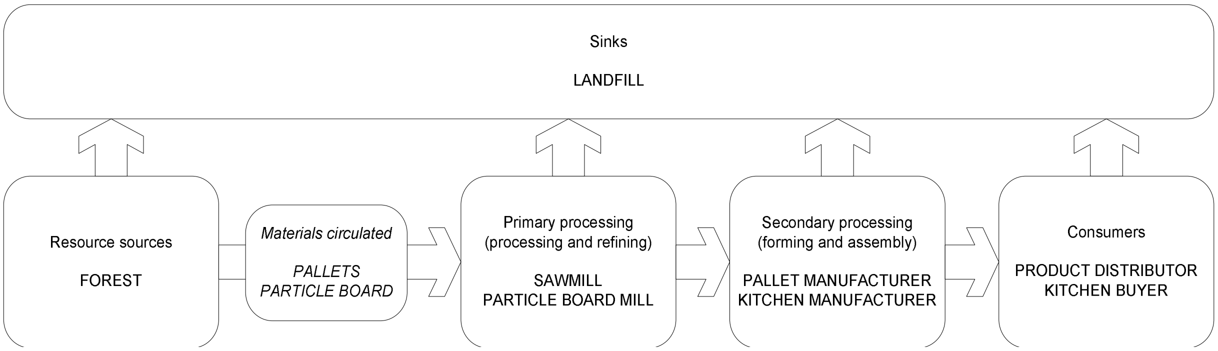

Figure 7-1 Creation of an industrial network from two distinct supply chains

7.3.3 Outline of Potential Industrial Network

The *resource-based view* (see Chapter 3) is adopted to explore 1) how wood consumption can be lowered by substituting virgin raw material with secondary material and 2) where wood waste may be integrated in other wood-based life-cycles. However, this system view is extended to consider further opportunities for integrating waste within the *region*. The wood case study is a particular case where the raw material and the product material characteristics do not differ greatly and the resource-based view is therefore still appropriate for looking at options for waste reintegration. If one would compare this with a case study where the intent is to avoid plastic waste, it would be useful to look first at other *plastic* using applications, i.e. supply chains that use the same material, rather than at other *oil*-based products, i.e. supply chains that use the same resource. This is because the material characteristics of plastic are substantially different form those of other petroleum industry products, such as fuels or lubricants.

Particleboard production is attractive from an environmental standpoint as particleboard are primarily produced from plantation thinnings and other timber processing waste, such as chips from sawmilling, where chips constitute about two-thirds of sawmill waste. However, this environmental benefit is off-set by the addition of adhesives and the increased energy requirement for production compared to timber processing. In addition to the adhesives, the durability of particleboard is often increased by adding fire retardants, fungal deterrents and surface finishes, which further complicate reuse and recycling (Attiwill et al., 2001). About three quarters are treated with veneers (Taylor et al., 2005). A number of options are available for particleboard recycling, including:

- Re-processing into new particleboard
- Breakdown for use in garden products
- Use as fuel in energy generation.

Being made of untreated, whole timber, the end-of life options are greater for pallets than for particleboard, as there are no chemical contaminants apart from those acquired during use. There are also options to integrating the waste generated during sawmilling to produce the logs needed for pallet manufacture. Reintegration options identified are (Attiwill et al., 2001):

- Reuse
- Recycling to different wood products
- Manufacture of garden products, such as mulch and compost
- Energy generation in the form of combustion to produce steam or combustible gas.

The production of ethanol as a fuel substitute is also been investigated (Botha and von Blottnitz, 2006; Cheng et al., 2008; Martin et al., 2002), but the necessary technologies have only recently become cost effective, principally due to the rise in energy prices. Other potential uses are activated carbon and impact absorbent playground material, although currently no facilities for activated carbon manufacture from timber waste exist in the SMA, and playgrounds only have a limited demand for wood waste. Playgrounds use mostly pine bark/mulch but less than 3% of playgrounds currently make use of wood chips (Martin and Cooper, 2005). Pallets can also be used, when chipped, for animal bedding and litter, and, when whole, for sale as firewood. Only untreated timber is suitable for these applications.

Wood wastes clearly have a large potential for reuse. As part of this case study, however, only larger scale applications are explored and, of those, only technology routes that are robust in regards to their raw material specifications, in other words that can handle contaminants and the resins contained in particleboard. This reduces the need for extensive sorting, and reduces some of the associated costs to enable reintegration. The reason only robust larger scale processes are included is that these facilities can a) take large quantities thereby effectively reducing waste to landfill, and b) can mix the wood waste with other raw materials thereby alleviating or avoiding any negative impacts the wood waste might have on the process. These facilities are therefore also less vulnerable to fluctuations in wood waste availability than facilities relying solely on wood waste. The chosen reintegration options are discussed in the next section.

This case study also highlights the constraints that material characteristics, an industrial network characteristic discussed in Chapter 3, impose on sustainable development strategies. In this case study the material characteristics influence the degree to which reintegration can be achieved, in this case through closed loop recycling. The reason that closed loop recycling is not as common in the wood industry as it is in the metals industry, for example, is that timber, unlike metal, cannot be recycled back to its original product specifications, e.g. a stack of particleboard cannot be converted back into the original log (Wibberley, 2002). The material properties therefore constrain the material allocation in the network, in other words the destinations to which waste material can be sent. Old pallets can be sent to particleboard manufacture. However the same is not true in reverse, as particleboard does not fulfil the structural strength requirement for pallets.

7.3.3.1 Closed loop recycling for pallets

If handled with some care, hardwood pallets have a lifetime of around three years. The transport of products, even over longer distances within Australia, ties pallets up in use for anywhere from a few days to nearly a month, after which it should be possible to reuse pallets directly numerous times unless they have been damaged. Due to differences in their material strength, hardwood pellets tend to last longer than softwood pallets. Once pallets are too damaged to be reused any further, they can also be used as another raw material source for particleboard.

7.3.3.2 Closed loop recycling for particleboard

Particleboard, in the form of kitchen cabinets, is laminated, cut to size, and assembled according to individual kitchen specifications and owner taste. As a part of the construction / demolition waste stream, the boards are not suitable for reuse. However, by breaking down the particleboard, roughly to its original fine grains, the particleboard could be recycled into new particleboard. Ring flaking, a process where wood is chipped into finer particles through a rotating ring of knives, in addition to hammer milling, is applied to break down material. Metal contaminants, such as nails and hinges, can be removed through magnetic separation, while other contaminants, such as paper, plastic and grit, are removed by sifting, air sorting and chip washing. This form of pre-treatment is commonly employed by facilities utilising recycled material. Techniques to remove the remaining contaminants, namely coatings and binders, have been developed and are being used in Europe, however, the technologies still yet to be introduced in Australia.

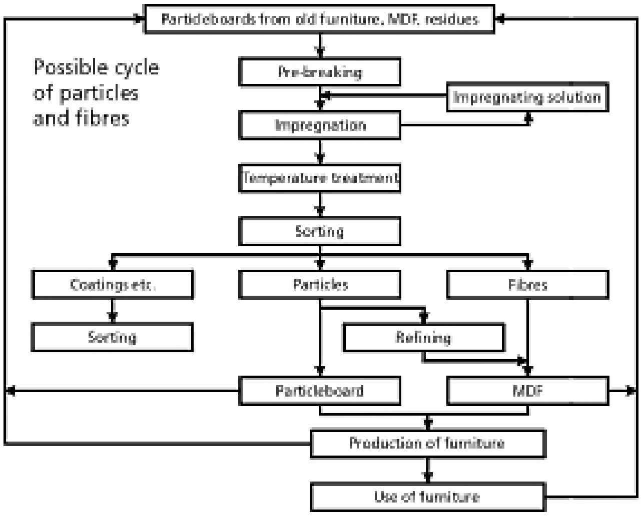

Figure 7-2 Flowchart for the WKI recycling process (http://www.wki.fraunhofer.de/projekte/wki-6-2e.html)

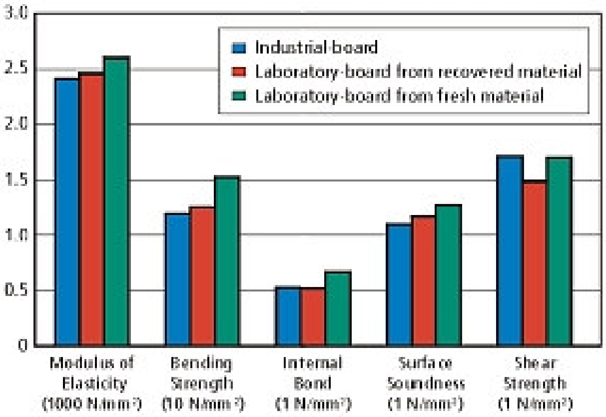

Figure 7-3 Comparison of structural properties of recycled board with board from fresh material and industrial board (http://www.wki.fraunhofer.de/projekte/wki-6-2e.html)

The Wilhelm Klauditz Institute (WKI) in Germany has developed and patented[26] a process using pressurised steam to break up the composite material, allowing ready separation of coatings and contaminants from the material[27] (Figure 7-2). This is followed by thermo-chemical pulping to complete the composite material break-up. The WKI claims a recovery rate of up to 95%. The recycled material can then again be processed with the conventional technology. While the thus manufactured particleboard had lower bending strength, it still has adequate internal bond strength and meets Australian standards (Figure

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[26] European patent EP 0 647 693, US patent 5705542

[27] http://www.wki.fraunhofer.de/projekte/wki-6-2e.html

7-3). The recovering process can be carried out repeatedly. As an added benefit, waste liquors generated during the digestion process can be used as binder, making the process a closed cycle.

Another process is Fibresolve[28], which uses extensive wetting and pressure-vacuum cycles and steam to break up the material. Research suggests that up to 97% can be recovered, and that process water and air emissions are minimal (Kearley and Goroyias, 2004). Micro Release[29] has been developed in conjunction with Fibresolve and uses a similar methodology, however, it utilises microwaves to break up the particles instead of pressure-vacuum cycles and steam. Micro Release is believed to be more energy efficient that Fibresolve, but has to date only been explored on a laboratory scale.

7.3.3.3 Reintegration of processing waste

Apart from end-of-life material reintegration, there also exist opportunities to use waste accumulated during pallet and particleboard production. Woodchips, which constitute around 35% of sawmill product, are already commonly sent to composite material manufacture, such as particleboards. Sawdust from sawmilling can be used for onsite energy, but is in many cases composted or landfilled. A panel mill will lose around 18% of material as sander dust, which is handled similarly to sawdust (Jaakko Pöyry Consulting, 1999).

7.3.3.4 Open loop recycling

Three open loop recycling options in the SMA are included:

- Process heat, for instance in cement kilns
- Power generation
- Mulching and composting

Heat: Wood waste is also increasingly being used as an alternative heating source for cement kilns (Foster and Collins, 2004; Warnken, 2001). As cement kilns operate at extremely high temperatures, there is very little ash left. The remainder is mixed in with the clinker and remains bound in the matrix of the cement. One issue with the burning of waste wood, both for heat and energy generation, is contamination. Metals and grit can lead to slagging, which reduces both efficiency and creates waste that may be an issue for disposal. Proper pre-treatment and sorting are therefore necessary. Emissions, such as volatile organic compounds (VOCs) do not appear to be a problem and are comparable to those of incinerating pure wood when the particleboard is fired at temperatures of between 500°C and 1000°C (Risholm-Sundman and Vestin, 2005).

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[28] www.fibresolv.co.uk

[29] www.fira.co.uk

Power generation: The use of wood waste for energy generation is attractive as it is capable of substituting fossil fuels such as coal, and reducing greenhouse gas emissions both through avoiding CO_2 emissions from coal fired power and by reducing the methane emitted when wood waste is landfilled. Use of wood waste for energy generation has several advantages over its use for heat, including the ability to use the energy for a wider range of applications. In 1999, Liddell Power Station (Macquarie Generation), approximately 160km north of Sydney, became the first coal-fired power station licensed to co-fire untreated wood waste Australia. At the end of 2003 it was still the only power station using wood waste. Delta Electricity is also licensed to co-fire up to 5% by weight, and is able to utilise both sawmill residue and C&D wood waste, which would include particleboard (Flood, 2003). In order to co-fire C&D waste, extensive testing of trace elements for each batch of wood waste and air emissions testing is required.

Power generation has, in some instances, turned out to be a source of competition for the production of composite materials, as a combination of renewable energy credits and high spot prices for power have made it more profitable to generate power for sale to the grid than to produce particleboard (Taylor et al., 2005).

Mulching and composting: Mulching and composting operations can accept untreated timber that is not otherwise saleable. Composite materials can also be used in some garden products if mixed with sufficient quantities of untreated timber (NSW Waste Boards, 2000). Otherwise waste wood can be diverted to green waste mulching operations (Nolan ITU Pty Ltd, 1999). The complete configuration of the wood products network including these technologies is shown in Figure 7-4.

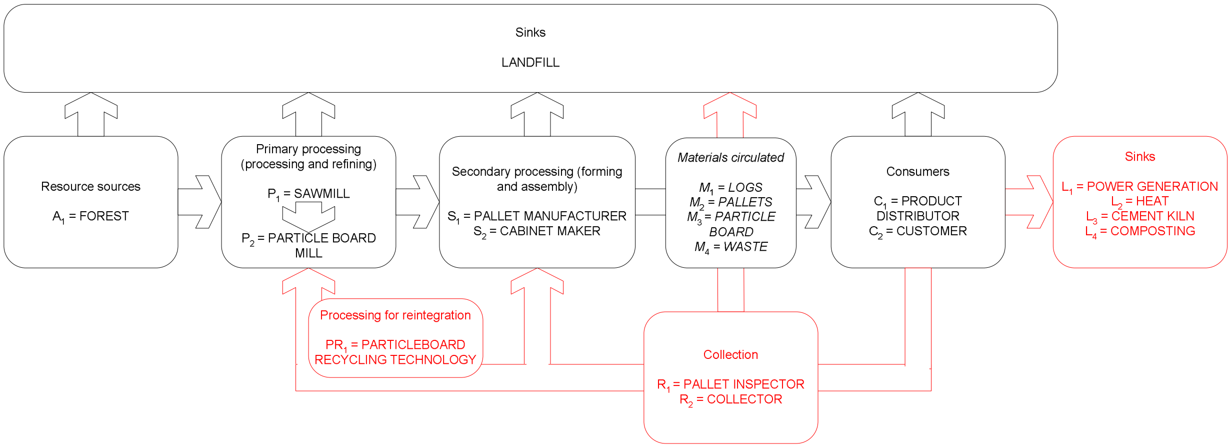

Figure 7-4 Extended wood products network boundary, including the greater integration and addition of open loop recycling alternatives. (Legends are explained in section 7.3.6)

7.3.4 Choice of Objectives and Indicators

The aim put forth in the problem statement was **to improve the material efficiency of the wood processing industry in the SMA, while ensuring that other environmental impacts are kept as low as possible.** The next step is to decide on indicators that can be measured, and which adequately reflect this objective. Three indicators were chosen that cover all aspects of the above material efficiency requirement:

- Profit, to reflect utility,
- energy consumption, to reflect other environmental impacts and
- material efficiency.

The material efficiency indicator is an example of how the sustainable development issues facing a network influences choice of indicators. This indicator is intended to monitor the success of the reintegration strategy. Social considerations are not included in this case study, as the proposed reintegration strategy and a resulting reduction of wood waste disposal and wood consumption are not expected to have a significant social effect.

7.3.4.1 Profit

As a reflection of the utility of the network overall profit for the network is recommended as an indicator. The monetary value of a product is often seen as a reflection of the desirability and functional value of that product, and can thus be used as a proxy for utility. A facility, supply chain, or network will only be economically viable if the costs do not exceed the revenues; in other words, if it generates an overall profit. In addition to the normal costs and revenues, the price of the equivalent in coal substituted through the use of waste wood in open loop recycling is credited to the network.

$$P = -CI_{PB} + \sum_{t=1}^{t=T} \sum_{i=1}^{i=I} \left((r_i - c_i) x_{i,t} \right) \tag{7-1}$$

P	- network profit	
CI_{PB}	- capital investment for particleboard mill (if applicable)	[AU$]
r_i	- revenue incurred by product stream of facility *i*	[AU$/t]
c_i	- operating and transport cost incurred by product stream of facility *i*	[AU$/t]
$x_{i,t}$	- mass flows at time *t*	[t]
$i = [1, 2\ldots I]$	- facilities in network	
$t = [1, 2\ldots T]$	- time step	

Only the capital costs for the particleboard recycling are considered as it is assumed that all other infrastructure already exists.

7.3.4.2 Energy consumption

The delivery of products also involves processing, manufacturing and transport, all of which have an impact on the environment. In the case of timber processing for pallet manufacture, there are few environmentally harmful material inputs or emissions. The same is true for particleboard, where the formaldehyde resin appears to be neither an issue in direct particleboard recycling or in burning or composting, as indicated in section 7.3.3.2 and 7.3.3.4. Wood processing requires energy. Timber and particleboard manufacture require heat for drying, which is energy intensive, as is the transport of the timber and timber products. Two open loop recycling options, namely power station and cement kiln, require wood for energy. It is assumed that the energy demand is satisfied by coal if the wood waste is not sent to these applications, and that every ton of wood waste is able to substitute an energy equivalent amount of coal. The mining and transport energy required to deliver coal is therefore credited to the network if a net energy equivalent amount of wood waste is sent to energy generating applications.

$$E = \sum_{t=1}^{t=T} \sum_{i=1}^{i=I} \left((e_{t,i} + e_{p,i} - av_i) x_{i,t} \right) \qquad 7\text{-}2$$

E	- network energy demand	[MJ]
$e_{t,i}$	- transport energy incurred by product stream of facility *i*	[MJ/t]
$e_{p,i}$	- processing energy required to deliver product stream of facility *i*	[MJ/t]
av_i	- energy consumption averted/energy savings (applicable to open loop recycling)	[MJ/t]
$x_{i,t}$	- mass flows at time *t*	[t]
i = [1, 2… I]	- facilities in network	
t = [1, 2… T]	- time step	

7.3.4.3 Material efficiency

Material efficiency can be captured by a number of different indicators. The effectiveness of the material loop closure and avoidance of virgin resource use is ascertained by using Dahlstrom and Ekins (2005) material efficiency definition i.e. material output divided by material input. This indicator has the benefit that, by maximising material efficiency, forestry impacts such as land clearing, erosion etc are mitigated through the increased use of secondary materials. This ratio cannot be applied directly, however, as the open loop recycling options generate both electricity and heat, and energy efficiency and material efficiency ratios are not directly comparable. Heat generation would otherwise always be favoured over electricity production. To overcome this problem, the following alternative is suggested: The electricity or heat produced by open loop recycling is instead represented as the equivalent amount of coal that would be required to generate that energy. In the material efficiency calculation, the material output is thus the sum of the pallet and particleboard produced, plus the amount of coal averted (representative of the energy produced) by sending waste to the open loop recycling options. The only material input to the network is forestry timber. Compost production is exempt in this case, as it is produced in any case from waste products. There is no resource benefit to be had from sending wood waste to composting as it would only replace other waste. For the dynamic problem, the material efficiency is the summed efficiency of each time step and divided by the total time, giving an average efficiency (Equ. 7-3).

$$\eta = \frac{\sum_{t=1}^{t=T}\left(\frac{x_{p,t}+x_{pb,t}+x_{ceq,t}}{x_{f,t}}\right)}{T} \tag{7-3}$$

Where $x_{ceq,t} = \frac{LHV_p}{LHV_{coal}} x_{p,ol,t} + \frac{LHV_{pb}}{LHV_{coal}} x_{pb,ol,t}$ 7-4

η	- network material efficiency	
$x_{p,t}$	- pallet mass flows at time *t*	[t/yr]
$x_{pb,t}$	- particleboard mass flows at time *t*	[t/yr]
$x_{ceq,t}$	- equivalent coal mass flows at time *t*	[t/yr]
$x_{f,t}$	- forest timber mass flows at time *t*	[t/yr]
LHV	- lower heating value (pallets (p), particleboard (pb))	[MJ/t]
$x_{p,ol,t}$	- flows of pallets to open loop option at time *t*	[t/yr]
$x_{pb,ol,t}$	- flows of particleboard to open loop option at time *t*	[t/yr]
t = [1, 2… T]	- time step	

Process impacts are allocated to the product stream. Processing impacts of a particular facility are only allocated to the immediate product streams, as it is due to the demand for the products that the material is processed in the first place. Flows to landfill are therefore not allocated process impacts; they only incur gate fees and transport impacts. Flows to open loop recycling are credited with impacts avoided by replacing the energy equivalent amount of coal needed for that application.

7.3.5 Choice of Scenarios

Scenario analysis was recommended in Chapter 6 as a means to consider uncertainty in the system and in future developments, i.e. to explore judgements regarding what is included in the boundary, how the network is linked, what indicators are included, or if the network operates in a changing technical or economic environment. The following scenarios address uncertainty about the reintegration structures chosen, or the extent to which reintegration may be adopted. This uncertainty concerns network structure and is therefore a system uncertainty.

Five scenarios looking at different degrees of network integration are generated for this purpose and network performance optimised within the given constraints.

- BASE: The base case, in which the performance is optimised within the current structure of the system that was illustrated in Figure 7-1.
- OPEN: A supply chain linkage scenario, in which the open loop recycling options are considered, but integration of materials between the supply chains is not available. Waste material can be collected and also used for open loop recycling.
- WASTE: The same structure as the OPEN scenario; however, waste is not collected but continues to be disposed to landfill.
- CLOSE: In this scenario, only the linkage between the supply chains is considered, whereas the open loop recycling options are ignored. Waste material is disposed to landfill.
- RE: The resource efficient case, where all options are available, as shown in Figure 7-4.

The results of the scenario analysis will be used to asses how performance is affected if some reintegration structures are adopted over others. The performance of the network under these five scenarios will consequently provide an indication of which strategies provide the greatest improvement from the base case, allowing a preferred network structure and performance to be identified.

7.3.6 Model of Wood Products Network

As described in Chapter 5, the network elements units can be classified according to their generic industrial network function:

A = [forestry]	Resource sources	7-5
P = [sawmill, particleboard mill]	Primary processing	7-6
S = [pallet manufacturer, cabinet manufacture]	Secondary processing	7-7
C = [product distributor, customer]	Consumers / markets	7-8
R = [pallet inspector, collector]	Collection for reintegration	7-9
PR = [particleboard recycling technology]	Processing for reintegration	7-10
L = [landfill, power generation, composting, cement kiln]	Network sinks	7-11

The material circulating within the network can be classified into four general types.

$$M = [\text{timber, pallets, particleboard, wood waste}] \qquad 7\text{-}12$$

Where "timber" refers to the virgin material delivered from the forests and plantations, "wood waste" refers to processing waste and end-of-life products, "pallets" and "particleboard" refers to new as well as reused products (in the case of pallets) or products manufactured from recycled material (in the case of particleboard). This classification has been used to represent the network in Figure 7-4.

The detailed wood products network used in the model as the basis for the mass balances is shown in Figure 7-5. The network structure shows all existing linkages, as well as possible new ones, and therefore corresponds to the scenario RE discusses in section 7.3.5. The structures for the remaining scenarios are shown in Figure 7-6. The newly added links, indicated in red, are the reuse of pallets, recycling of old pallets to the particleboard mill, recycling of particleboard, collection of waste and allocation to open loop recycling. As the sawmill waste to particleboard mill link already exists, it is included in all scenarios. It has to be emphasised that the optimisation is free to chose which linkages will be active and to what extent material flows along these linkages.

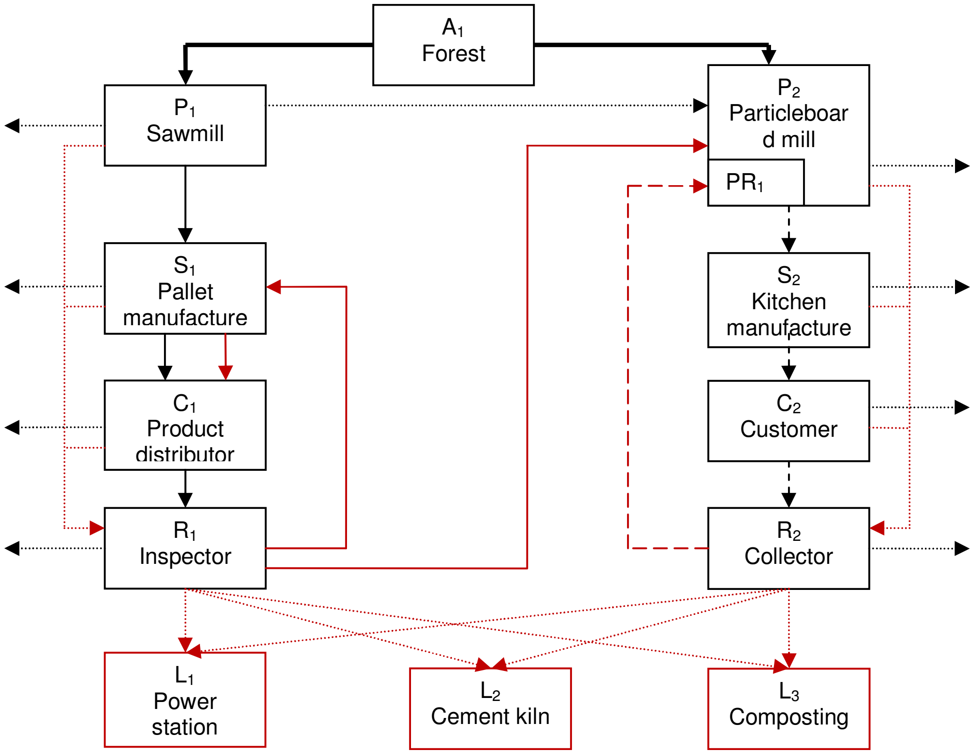

Figure 7-5 Detailed illustration of wood products network. The illustration shows all possible flows, which corresponds to the RE scenario. The dashed lines indicate particleboard flows, the bold lines timber and the dashed lines waste and secondary material. New facilities and links are highlighted in red.

The network flows are driven by the demand for pallets and cabinets, which have to flow into the market product deliverer and the kitchen customer (C_1 and C_2). While particleboard demand is assumed to fall (by 35% over 40 years, or 20% over 25 years (Stafford and Neilson, 1996)) the number of households in the SMA has increased, from 944,200 in 1996 to 1,035,400 in 2006, which is a rise of nearly 10% (Australian Bureau of Statistics, 2006). With a growing number of households, the number of kitchen cupboards would also be assumed to rise. However, whether the material of choice will be particleboard is unknown. To compensate for these considerations, a demand decline of only 10% over the model time frame is assumed. Pallet demand on the other hand is expected to grow at a rate of 5% per annum, similar to other timber products (ABARE, 2006; Attiwill et al., 2001).

Time steps are in monthly increments. Pallets are released after 1 month and particleboard after 216 months in the use phase (corresponding to 18 years). This assumption is based on German market research on kitchen life times, however, it is assumed that this data is comparable to Australian (GfK, 2006). The total model time frame is 300 months (25 years) to span kitchen cabinet lifetime.

Costs for the system include the price of transportation, landfill disposal fees, recycling centre fees and operating costs. Capital costs are only incurred if particleboard recycling technology is included. Revenues in the network are only generated from the sale of final products, i.e. cabinets and new and second-hand pallets. The costs of forest timber, sawn timber, chips and particleboard is assumed to cancel out on the network level, as the money is transacted from one node to another. Cost benefits are possible if material is sent to the power station and the cement kiln as the wood waste is cheaper than coal for the same amount of energy delivered. No such benefit is assumed for composting, as this process relies on wastes as its raw material and hence no benefit is incurred when sending material to this facility apart from the fact that wood waste sent here has further use.

Energy consumption includes the process and transportation energy in the network. Using wood waste to substitute for coal creates an energy benefit to the network by avoiding the energy required for mining and transportation to the SMA. All system equations, i.e. mass balances, as well as costs and energy requirements of the various processes and transport are discussed in Appendix D. This includes the assumptions underlying the equations and values used. The model is solved using GAMS/MINOS

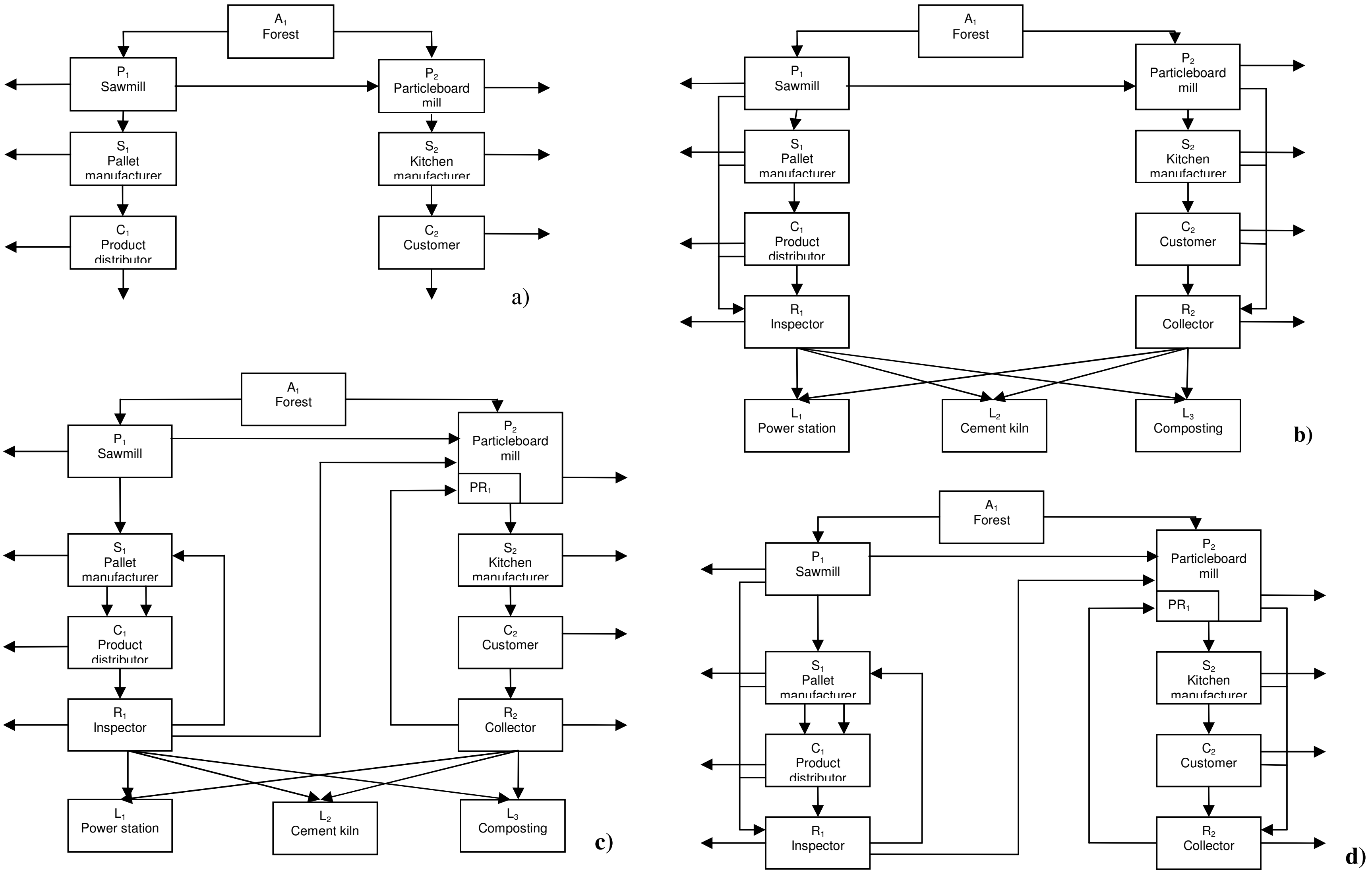

Figure 7-6 Possible flows for the various scenarios: a) base case (BASE): virtually no recycling,, except for sawmilling waste to particleboard production, b) only open loop recycling is possible (OPEN), c) waste is not collected, but sent to landfill (WASTE) and d) only closed loop recycling is considered (CLOSE).

7.4 RESULTS

7.4.1 Best Network Performance and Structure for Individual Objectives

Figure 7-7 to Figure 7-9 show the performance of the various scenarios with respect to the objectives of profit maximisation, minimisation of energy consumption and maximisation of material efficiency. The lowest cost, or rather highest profitability (14 million AU$), is achieved when any available waste material is sent to open loop recycling (RE and OPEN). Closed loop recycling is less attractive financially for the reason that collecting, examining and fixing second-hand pallets incurs costs, as does particleboard recycling, whereas selling waste material to open loop recycling facilities generates a small profit through coal substitution. Also, new pallets, rather than second-hand pallets achieve a higher price even if more processing, and hence cost, is involved in making these new pallets. Sending waste to open loop recycling contributes about 500,000 AU$ to the network profit.

The scenarios in which open loop recycling is considered also generate the best results with respect to energy consumption, creating significant energy savings (nearly 20 million MJ over 25 years). This is due to the energy savings that they create by substituting coal, the delivery of which requires significant energy. The base case has the highest energy requirements due to the fact that it processes virgin raw material and has no energy saving opportunities available. If closed loop recycling is possible, performance is better as pallet reuse provides significant energy savings due to the fact that it avoids the energy input necessary to otherwise process forest wood at the sawmill, and to manufacture pallets form the resulting timber (CLOSE). The absence of waste material for recycling contributes 30 million MJ over the 25 year time horizon.

The highest material efficiency is reached if the material can be recycled internally. Recycling to open loop facilities avoids a smaller amount of coal, only around 0.75 ton coal for every ton of wood sent to these facilities. As a result, the best performance is achieved in networks where closed loop recycling is possible (RE and CLOSE). The material efficiency score is dominated by pallet flows. Pallet demand is higher than particleboard demand, hence pallet flows are higher, contributing more. The lack of process waste lowers the efficiency by nearly 20% (WASTE). It is of little surprise that in the base case, and the scenario without the opportunity for closed loop recycling, performance is much worse.

In all cases of open loop recycling, the material was sent exclusively to the cement kiln. This is due to the fact that it averts the same amount of coal as if the material had been sent to power station, but the cement kiln is more closely located to the recycling centres (“collector” and “inspector”). Sending material to the cement kiln therefore incurs less transport costs and uses less transport energy. Consequently, all future references to open loop recycling in the wood products network imply burning of wood waste at the cement kiln.

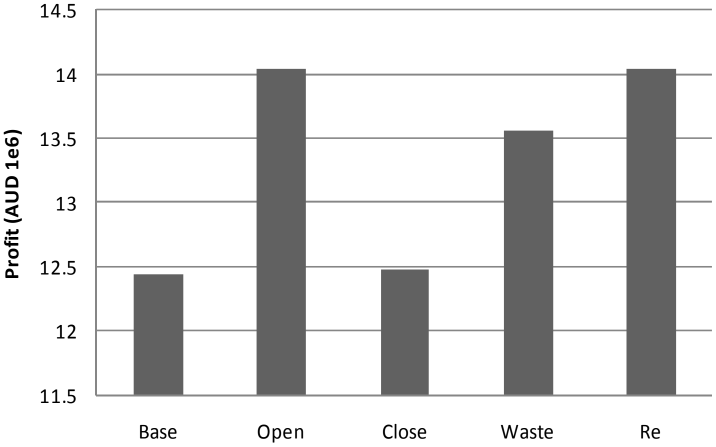

Figure 7-7 Highest profit possible within the five scenarios.

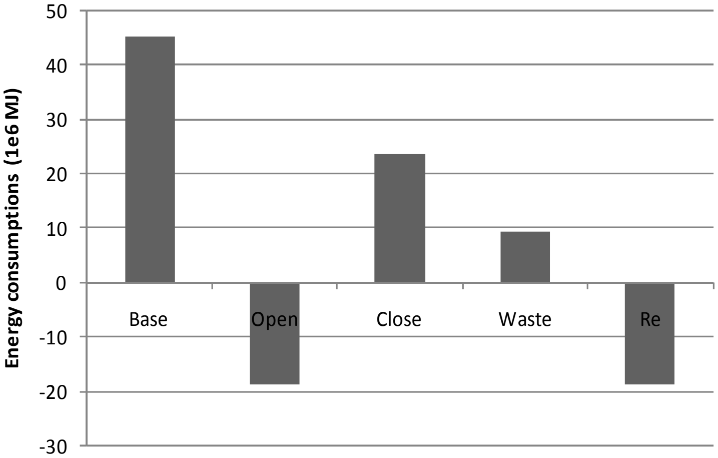

Figure 7-8 Lowest energy consumption possible within the five scenarios (Note: negative energy consumption represents an energy credit to the system)

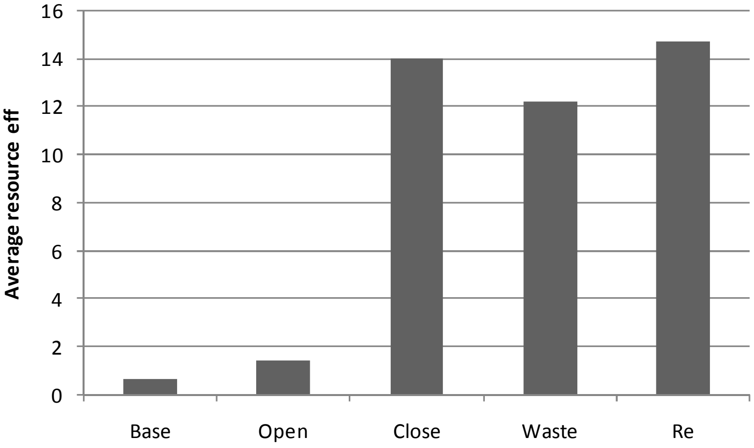

Figure 7-9 Best material efficiency possible within the five scenarios

The best performance with respect to all objectives is reached by the RE scenario. It has all options of resource allocation available and hence the best option can be chosen by the optimisation. However, the network structures that give rise to the highest profit, lowest energy consumption and highest material efficiency differ from each other. While the overall dominance of the RE scenario is an indication that the reintegration of material within industry is not only practicable, but also beneficial, further analysis is needed to determine if satisfactory performance can in actual effect be achieved with respect to all objectives simultaneously, or for several objectives without excessively sacrificing performance in other objectives. As only a single network structure can be implemented, the challenge lies in determining a network structure that delivers overall satisfactory performance. What constitutes "satisfactory", "excessive sacrifice" or "preferred overall performance" requires a degree of subjective judgement, in other words it has to be determined by the priorities of a decision-maker. The choice of the preferred overall performance is supported by multi-objective optimisation which shows the range of best possible performance and the trade-offs between the different objectives. This is looked at in the next section.

7.4.2 Multi-objective Optimisation

For the generation of the Pareto surface, the cost objective was retained, whereas the material efficiency and energy consumption were used as constraints (see description of ε-constraint method, Chapter 5). Overall, 121 single optimisations were performed to generate the surface. This was deemed sufficient as no great complexity is expected with a linear problem and a clear shape of the surface could be identified. Not all of these are included in the graphs as at many of the resulting constraint combinations no feasible solution exists

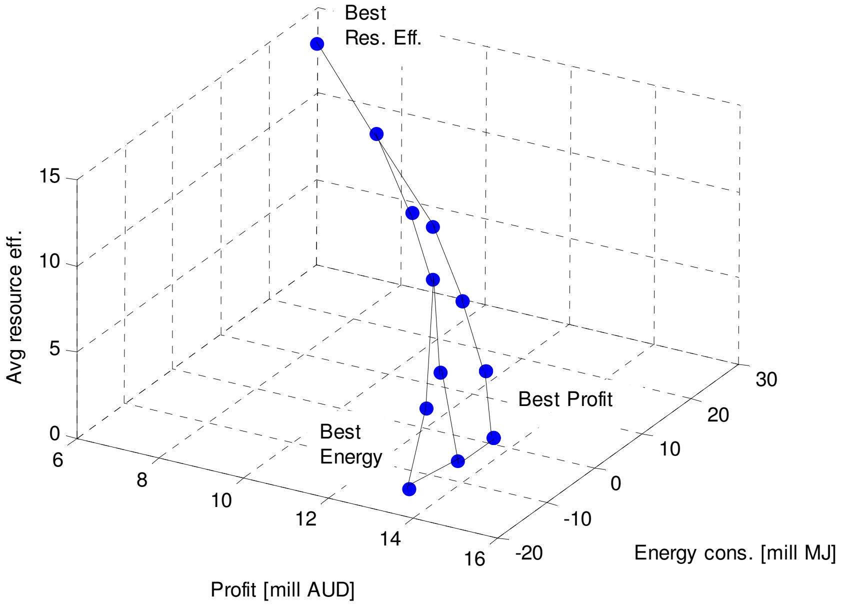

Figure 7-10 Pareto surface for the RE scenario

Figure 7-10 shows the Pareto surface for the RE scenario in a three-dimensional plot. The profit maximum, energy consumption minimum and material efficiency maximum form the edges of this surface, which presents the best possible system performance. Everything above this surface is physically unattainable, whereas any point below this surface represents suboptimal performance.

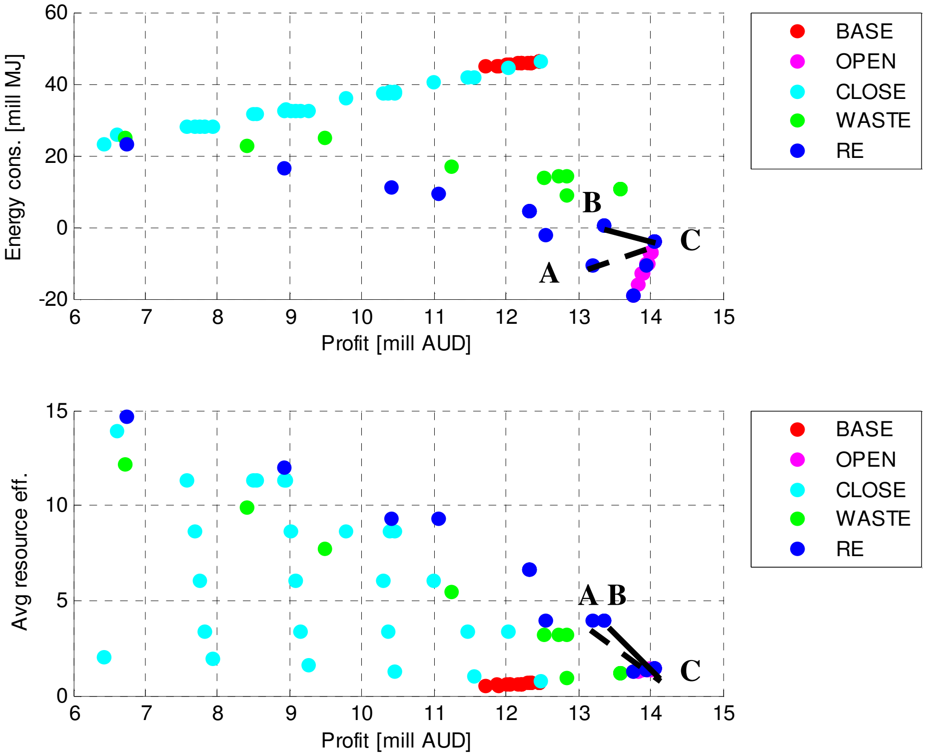

Figure 7-11 Two-dimensional representations of the three-dimensional Pareto surfaces of all five scenarios

The dominance of the RE scenario as well as the trade-off between the objectives, is clearly visible in the two-dimensional representation of the Pareto surfaces of the five scenarios in Figure 7-11. Figure 7-11 breaks the three-dimensional surfaces, like the one shown in Figure 7-10 into two two-dimensional representations to better show the spread of the possible performance. The RE scenario consistently has the lowest energy consumption, highest profit and highest possible material efficiency. The base case (BASE) has the worst overall performance due to the lack of recycling options which could reduce costs, save energy and raise material efficiency. The narrow operating range is due to the fact that the profit and material efficiency objective are one and the same point which is also the case for the OPEN scenario.

The waste scenario (WASTE) has similar performance to the RE scenario. However, energy consumption is consistently higher, by about 10 million MJ over the time frame of 25 years. Material efficiency on the other hand is consistently lower by about three points. The similarity lies in the fact that the RE and

WASTE scenarios have underlying network structures which do not substantially differ, the only difference being the lack of process waste materials for open loop recycling in the WASTE scenario. The OPEN scenario has a very narrow operating range and very low material efficiency due to the lack of opportunity for closed loop recycling, but due to the energy credits from substituting coal, the overall energy consumption for OPEN is lower than that of all other scenarios with the exception of RE. By the same logic, the base case and CLOSE scenario have the highest energy consumption due to the lack of open loop recycling and hence energy credit. The CLOSE scenario also has a good material efficiency performance, but lower then RE and WASTE due to the inability to open loop recycle any material. The broad range of possible resource efficiencies in the CLOSE scenario (ranging from 1 to 14) is the result of the low material efficiency achieved by of the profit and energy optima.

Another interesting point to note is that the trade-offs between the objectives are not consistent between the scenarios. Whereas RE and WASTE show a decrease in energy consumption with increasing profit, all other scenarios show an increased energy consumption. This is due to the fact that the RE and WASTE scenario can get both the energy credits from open loop recycling, as well as the energy avoided with manufacturing products from virgin materials through closed loop recycling primarily the reuse of pallets which reduces cost and creates added income.

Each point of the RE Pareto surface outperforms that of any other scenario, confirming that the RE scenario does in fact deliver superior performance. Increased material cycle closure can in fact improve environmental performance without incurring excessive cost. The challenge now lies in determining what point on the RE Pareto surface, i.e. what performance combination, is preferred. No one point on the surface dominates another and as a result the preferred network performance, and hence network structure, will have to be identified by prioritising between the objectives and by considering the possible trade-offs between the points. This exercise falls within the realm of multi-criteria decision analysis (MCDA), where relative weightings for different objectives reflect the value judgement of the decision-maker in terms of preference relationships (which, in turn, are a function of the specific performance scores for each of the scenarios in the selected objectives).

However, there are specific insights which can be derived from this analysis without resorting to a formal MCDA. An improvement in profit generally results in both reduced material efficiency as well as decreased energy consumption for the RE scenario. Consequently, an increase in energy consumption is associated with an increase in material efficiency. For instance, an increase in profits from seven to eight million AU$ results both in decreased energy consumption of 2 million MJ (from 21 to 19 million MJ), and a decreased material efficiency (from 14 to 13). However, towards the higher end of the profit scale, from 13 to 14 million AU$, energy consumption could both increase, if one were to move from A to C on the Pareto surface (dashed line in Figure 7-11) or decrease (solid line from B to C). Both moves are associated with performance losses in material efficiency. However, as the material efficiency scores of points A and B are nearly identical, B would be clearly preferable to A.

In light of these trade-offs, it would be preferable to move towards higher profit as this simultaneously results in lower energy consumption, which is desired. The limitation in this case would be the extent to which material efficiency is to be sacrificed (and it is here that an MCDA exercise would add value). If a net energy saving is to be achieved, i.e. energy consumption below 0, as well as profits exceeding those of the base case, then the material efficiency would not reach higher than 5. It could be argued that higher, i.e. positive, energy consumption would be acceptable, as this is still well below the energy consumption of the base case. However, the profitability would drop quickly below 12.5 million AU$. This would represent economic performance falling below that of the base case, which would be unacceptable to the network agents, as the losses would be borne by one or more of them. The preferred network performance is therefore set at the point on the Pareto surface with the following performance:

- **Profit**: 13.5 million AU$
- **Energy savings**: 0.2 million MJ
- **Average material efficiency ratio**: 3.3

While a material efficiency of 3.3 is roughly a fifth of what is (best) achievable, it still represents a three-fold improvement over the material efficiency of the base case. The network structure that gives rise to this network performance is described in the next section.

7.4.3 Preferred Network Structure

Figure 7-12 shows snap-shots of flows through the preferred network structure at two different times - 24 and 150 months - indicating how network operation changes. Virgin raw material is only supplied to the network for pallet manufacture in increasing amounts to accommodate the rising pallet demand. Particleboard, in turn, is manufactured predominately from suitable sawmill waste, such as chips, with the remaining raw materials supplied in the form of old pallets. The used pallets not going to particleboard manufacture are sent to open loop recycling rather than reuse. While this appears a waste of pallets, the motivation for this choice is the desire to maintain net energy saving. Therefore, the pallets are used for heat generation at the cement kiln along with any available process waste. After 180 months, or 15 years, the flow pattern is similar, even if the overall flow volume has increased. The major difference lies in the fact that at this stage pallet demand has outpaced particleboard demand to the degree that the sawmill waste provides sufficient as raw material and used pallets are no longer needed.

The flow of old cabinets from the customer market is slightly higher than the flow of new cabinets into the customer market. This is due to the predicted slow decrease in particleboard product consumption, meaning that, in the past more particleboard cabinets were bought, and are being released, than are acquired at the particular point in time.

Implementing this network structure and operation in reality may be associated with some practical problems that have not been included in the model: For one thing, does it make sense to fire pallets that have only been used once, in an attempt to substitute coal? What is beyond the scope of this network is the consideration of alternative fuels that could be used instead to replace the required coal. If the benefit of coal substitution would be disregarded in the model, pallet reuse would in all likelihood play a much more important role. Whether this is true, and to what degree this applies, will have to be revealed by the uncertainty analysis in the next section.

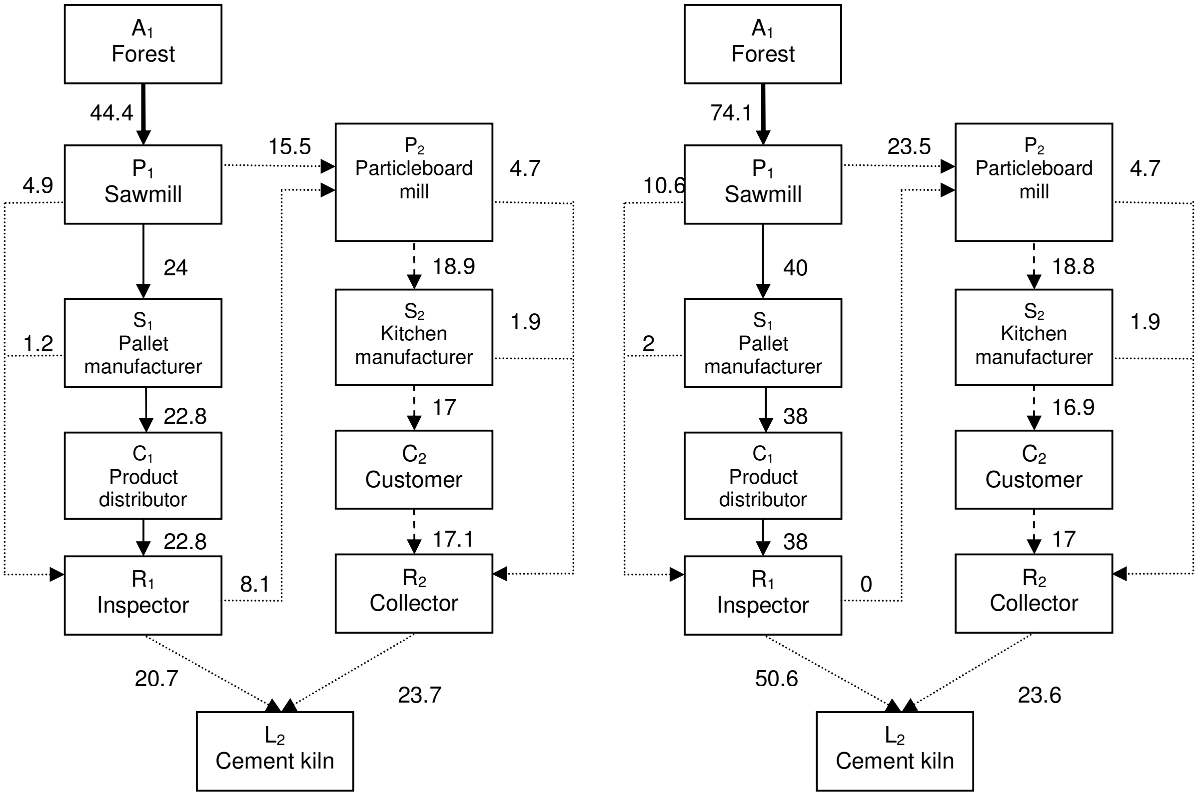

Figure 7-12 Network structure and flows at 24 and 150 months.

The following section will deal with the effect of uncertainties in assumptions such as this one. In fact, it will be shown that the coal substitution assumption is one of the most important parameters influencing the material efficiency score and the most important parameter influencing energy consumption.

7.5 CONSIDERATION OF UNCERTAINTY

The information used to describe this regional network had to be drawn together from a wide range of sources. As far as possible, information was used that described wood industry performance in the SMA; however, in those cases where the necessary data could not be found for the wood industry in the SMA specifically, other sources providing Australian aggregate industrial or international data had to be used. The use of aggregate, out-dated data, and information from other contexts, introduces significant uncertainty. It therefore has to be determined how robust the deterministic results are in the face of uncertainty, in other words, if other possible model forms and parameters are considered, to what extent will the network performance be effected, and will the recommended network structure change?

Model form uncertainty, as discussed in Chapter 6, comes in three types, uncertainty in future events, system uncertainty, and uncertainty in mathematical expression. Future and system uncertainty, as defined in Chapter 6, are captured by scenario analysis. In this case study, system uncertainties included lack of knowledge about how reintegration options influence network performance. The results of the scenario analysis showed that the RE scenario, where all reintegration options are available, is able to deliver the best performance with respect to all chosen objectives. As a result this scenario is taken forward for detailed uncertainty analysis, assessing the impact of uncertainty in mathematical expression, and in model and empirical parameters.

7.5.1 Model Form Uncertainty: Mathematical Expression

This section focuses on uncertainty in mathematical expression. The network is described by three types of equations: mass balances that govern material flows and allocation; demand curves that represent a driver for the system (in addition for the desire to increase material efficiency), as well as performance equations that describe the yield of the individual processes and those that correlate flows in the system with costs and energy consumption. In this case, no serious issues could be identified concerning the equations used to describe the system and its performance and no viable alternative model forms could be identified. Only uncertainties about the parameters used in the equations could be determined. Mass balance closure is a physical law and as a result overall mass balance equations around the network nodes cannot be uncertain[30]. The costs, energy consumption and conversions are represented by linear equations (Equations 7-1 to 7-3). While the linear equations could be replaced by ones that accounts for economies of scale, where the per unit cost/energy consumed decreases with increasing scale, this effect is assumed

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[30] This is in regards to input equals output. How the material coming in is converted may well have underlying uncertainties, but in this case uncertainty in conversion efficiencies is captured as empirical parameter uncertainties.

to be negligible over the range of flows in the network. Of biggest concern is the product demand, and the underlying assumptions used to define its rate of growth. The demand governs the flows in the network over time and, as a result, changes in this are anticipated to have a significant effect on performance that should be explored. However, there is no information available that suggests a different form, merely different rates. As a result, this is an uncertainty to be handled by empirical parameter variation, as the growth rates are theoretically measurable quantities.

7.5.2 Parametric Uncertainty

For all values used in the model, ranges of possible values were cited, or could be estimated. As this represents a substantial set, a sensitivity analysis was performed to determine the parameters' respective importance, in other words the extent to which each affects the performance with regards to each objective. Fractional factorial design (FFD) is used for this purpose in this case study. A deviation of more than 10% from the outcome of the deterministic model is deemed significant in this case.

While FFD can simultaneously assess the influence of both model, as well as empirical, parameters, only empirical parameters were included in this case. The wood products model contains few model parameters compared to empirical parameters, in this case model time frame and time increment. The model time frame (300 months) and the time increment (1 month) are also model parameters, but varying these are not anticipated to alter network structure or development pathways significantly or to reveal additional insight, so they are excluded from the uncertainty analysis. The importance of the demand curves was briefly discussed in the previous section. As a result the demand growth rates were excluded from the FFD but are considered in the uncertainty modelling which is discussed in the next section.

7.5.3 Outcomes of Parameter Importance Testing

Table 7-1 shows the importance ranking of the set of parameters that affect, or may affect, the material efficiency objective. The importance of an uncertain parameter is determined by the deviation from the expected objective value or optimum which the parameter variation has caused. The results illustrate clearly how significant the influence of uncertainty is with regards to the model outcomes. Very few parameters have importance of less than 10%, i.e. the model parameters "best" and "worst" values change the model outcome by less than 10%. Only variation in the initial value of particleboard demand contributes less than 8% deviation to the model outcome, and could thus be ignored. This can be attributed to the fact that, firstly, total particleboard flow is lower than that of pallets, and hence contributes less to network performance. Also, a change in particleboard demand is not anticipated to have an affect on network structure: For maximum material efficiency, as well as lowest energy consumption, particleboard is not recycled, it is always more attractive to open loop recycle. Without a change in underlying network structure, the material efficiency may therefore be less affected. Overall, the parameters influencing the flow of pallets have a much greater effect than those referring to particleboard flows. This is due to the greater demand for, and hence greater amount of pallets circulating in the system. One exception is the timber conversion to pallets, which has a contribution of 20%. This comparatively low contribution results from the low flow of forest timber used when the resource ratio is maximised: In this case the demand for pallets is satisfied as much as possible from reused pallets.

As was pointed out in the previous section, the coal equivalent substituted is the third most important parameter influencing material efficiency performance. If the amount of coal substituted by every ton of wood waste were to change, or even set to zero (meaning no coal would be substituted through the use of waste wood, or, equally, that power from combustion of wood waste was additional to the total power pool) then the network performance, but also network structure, will change. Open loop recycling would no longer be considered to contribute to material efficiency, or only contribute a little, as in this case.

It is important to note that, while timber conversion into pallets and initial demand for particleboard have a relatively small contribution to the outcome of the material efficiency optimisation in this case, this may no longer hold for another model configuration. If, for instance, particleboard flows were to be comparable or even higher than pallet flows, the ranking of important variables would change. A sensitivity study would thus have to be repeated for different model forms.

Table 7-1 Importance of the parameters influencing material efficiency

PARAMETER	DEVIATION (%)
Maximum reuse fraction of pallets	292
Forest logs conversion to timber	171
Coal equivalent substituted through pallets	152
Use duration pallets	138
Initial demand pallets	124
Old particleboard conversion to new particleboard	121
Chips/pallets conversion to particleboard	110
Coal equivalent substituted through particleboard	70
Forest logs conversion to chips	53
Particleboard conversion to cupboards	53
Use duration of particleboard cabinets	47
Forest logs conversion to particleboard	30
Timber conversion to pallets	20
Initial demand particleboard	8

Similar results, which are shown in Table 7-2 and Table 7-3, can be observed for the FFD performed for the cost and the energy consumption objectives. The cost objective is dominated by prices that can be achieved for new and second-hand pallets, and for particleboard. The initial demand for pallets is also a crucial factor, as the availability of pallets in the network has great potential to save costs through reuse and recycling. Transport distances also have a significant influence on network performance. Overall, parameters describing particleboard flows are less important than those pertaining to pallets due to the lower flow rates of particleboard over the 25 year model time frame.

For the energy consumption objective, the dominant parameters are the amount of energy that can be saved through open loop recycling of both pallets and particleboard by substituting coal. Transport energy, i.e. distances and energy consumed per load and kilometre are also significant parameters, and conversion efficiencies play a more significant role than they did with respect to the cost objective. Initial pallet demand is again important as this influences the quantity of material and hence overall energy needed to run the network or amount of coal that can be substituted. Initial particleboard demand plays an insignificant role, as it did for material efficiency.

The overwhelming majority of parameters have a significant effect on model outcomes, with contributions over 10% (shown in grey in Table 7-2 and 7-3). Very few parameters could therefore be eliminated. In order to be able to still deal with the uncertain parameters, three parameter sets are constructed: a "best" case, "worst" case, and the expected/deterministic case. This is in accordance with the approach to stochastic optimisation that was chosen to handle empirical parameter uncertainties in this thesis, and which was described in Chapter 5. In those situations where it is unclear whether a high value for a parameter has better or worse consequences, the high parameter realisation is included in the best scenario. Similarly a low parameter realisation is included in the worst scenario. The best case therefore also includes, for instance, the highest possible demand growth. High demand growth will raise costs as well as revenues hence no clear conclusion can be drawn about the effect of growth on the profit indicator. Similarly, the worst case includes the lowest possible demand growth. For the stochastic optimisation, the best, worst and expected states of the world are assumed to have a certain probability of occurring. An explanation of how the stochastic model is constructed is provided in Appendix C.1.1.

The results of the deterministic optimisation are then compared to the results of a stochastic model where the best, worst and expected realisations of the world have respective probabilities of 25%, 25% and 50%. To also obtain an indication of the entire range of possible performance of the network, performance for was optimised for the case that only the best/highest parameters are realised, and the case where only the worst/lowest parameters are realised in addition to the stochastic results.

Table 7-2 Importance of the parameters influencing cost

PARAMETER	DEVIATION (%)
Cost of new pallets	195
Initial demand pallets	132
Cost of cabinets	89
Cost of recycled pallets	85
Pallet manufacturer operating cost	68
Particleboard manufacture operating cost	60
Transport short distances	50
Initial demand particleboard	44
Particleboard recycling operating costs	37
Transport to particleboard mill	37
Forestry costs	33
Pallet manufacturer: re-use of pallets	33
Particleboard recycling capital cost	31
Forest logs conversion to particleboard	31
Sawmill/inspector to particleboard	30
Kitchen manufacture cost	30
Recycling centre fee (mixed waste)	29
Cabinet maker: particleboard to cupboards	25
Pallet manufacturer cost (recycled pallets)	25
Collector to particleboard fraction	24
Conversion of logs to chips	20
Raw material cost saved (coal)	17
Landfill fee (mixed)	16
Use duration pallets	15
Pallet manufacturer: timber to pallets	15
Inspector cost	12
Sawmill costs	12
Collector cost	5
Landfill fee (wood)	3
Recycling centre fee (wood waste)	3
Medium transport distance	2
Use duration particleboard	2
Sawmill: logs to timber	1
Raw material cost saved (coal)	1

Table 7-3 Importance of the parameters influencing energy consumption

PARAMETER	DEVIATION (%)
Energy averted through pallet open loop recycling	628
Energy averted through particleboard open loop recycling	533
Transport short distances	378
Chips/pallets conversion to particleboard	311
Initial demand pallets	285
Particleboard conversion to cupboards	283
Energy to repair pallet	276
Maximum reuse fraction of pallets	276
Forest logs conversion to timber	222
Sawmill energy	207
Energy of pallet manufacturer	198
Use duration particleboard	169
Timber conversion to pallets	139
Particleboard mill energy	107
Use duration pallets	66
Energy for kitchen cabinet manufacture	66
Forest logs conversion to chips	55
Old particleboard conversion to new particleboard	51
Medium transport distance	44
Particleboard recycling energy	29
Forest logs conversion to particleboard	23
Transport to particleboard mill	4
Initial demand particleboard	1

However, because the choice of probabilities is based only on estimates, it is necessary to assess the sensitivity of the stochastic model with respect to changes in the probability distribution. Two additional cases are therefore evaluated, where the best, worst and expected cases have the following probabilities, respectively:

- 33%, 33%, and 33%,
- 10%, 10% and 80%.

These distributions were chosen as they cover the different degrees of uncertainty of the expected case occurring, ranging from very uncertain (only 33% likelihood that the expected case will occur), to quite likely (80%). In these cases the worst and best realisation of the world are assumed to be equally likely. The sensitivity analysis would be more comprehensive if it included additional combinations (e.g. 20%, 20%, 60%), but also skewed distributions the where best and worst cases are not equally probable (e.g. 20%, 30%, 50%). However, the three combinations which will be explored, in addition to the deterministic case (which is identical to a probability distribution of 0%, 0%, 100%), the best case only and the worst case only, a good idea can be obtained about the effect of empirical parameter uncertainty on model outcomes. If results indicate a great sensitivity to the distribution of probability, then additional combinations can be explored.

7.5.4 Outcomes of Uncertainty Modelling

The optimal performance scores with respect to each objective for the "expected" or average data, which is also used in the deterministic analysis, "best", "worst", as well as the stochastic case are shown in Table 7-4.

The best and worst cases serve as an indication of the possible range of system performances that are possible. Figure 7-13 illustrates this: The figure shows the Pareto surfaces of the deterministic and the stochastic case, as well as results of the best and worst case scenarios. (The deterministic surface is the same as the one represented in Figure 7-10.) The network response to the best conditions delivers significantly better performance with respect to both profit and energy consumption compared to the deterministic case. The values in Table 7-4 show that the profit for the best case is over seven times higher than the expected case, whereas the profit in the worst case is "only" 10 % lower. A similar trend is observed for the energy consumption. As a result, as can be seen in both Table 7-4 and Figure 7-13, the stochastic optimisation shows better performance in these objectives compared to the deterministic solution. This is likely an artefact of the numbers used in the case study. The stochastic optimisation determines the best network performance in the face of the eventuality of the worst, best and expected scenarios occurring, whereas the deterministic solution merely relies on the average data.

Table 7-4 Best possible performance with respect to the three objectives for the expected, best, worts and stochastic optimisation.

	HIGHEST PROFIT (MILLION AU$)	LOWEST ENERGY CONSUMPTION (MILLION MJ)	HIGHEST AVERAGE MATERIAL EFFICIENCY
Expected case	14	-18.8	14.7
Best case	106.9	-132.7	16.1
Worst case	-1.2	2.2	1.4
Stochastic optimisation	24.5	-37	12.4

Profit and energy consumption increase so strongly in the best case not only because of high revenue and low costs (low energy consumption and high energy credits) per unit material handled in the network, but also due to the higher overall mass flows of materials. Material efficiency, on the other hand, is based on the amount of material reused in relation to the amount of material supplied to the network. As this ratio is less inclined to increase with increasing overall flow, the average material efficiency does not increase compared to the expected solution. For the worst case on the other hand the conversion efficiencies at the facilities were assumed to be low. As a result, there is little end-of-life products available for closed loop recycling, the major contributor to a high material efficiency, and a much larger fraction of material is collected as waste and this can only be open loop recycled. This drives downwards substantially the material efficiency that can be achieved.

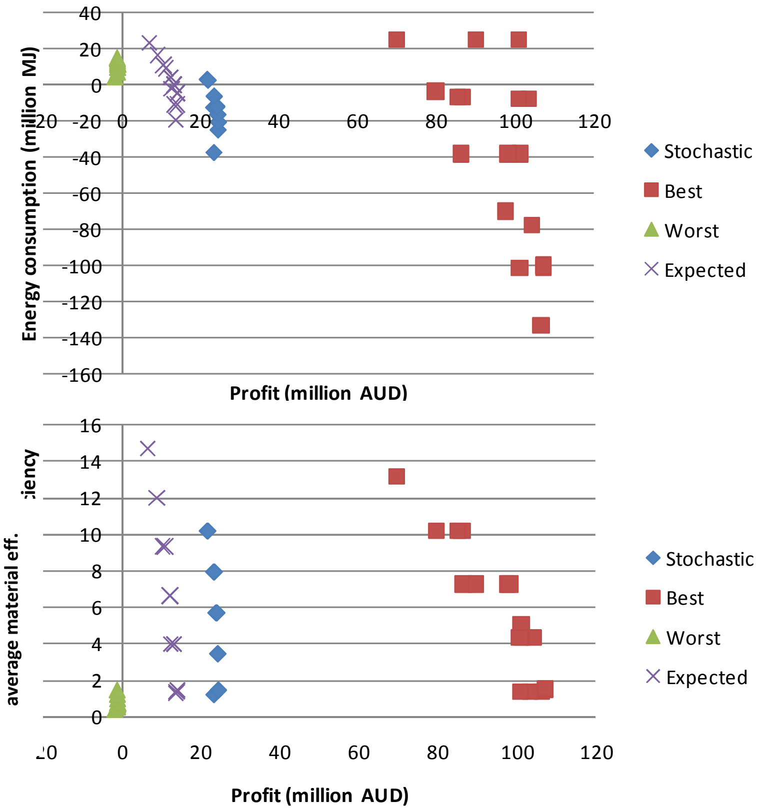

Figure 7-13 Pareto surfaces for the stochastic, best, worst and expected cases

It appears that the deterministic case was a conservative assessment due to the fact that the stochastic optimum exceeds the performance of the deterministic case with respect to profit and energy consumption, with little sacrifice in material efficiency. This is due to the fact that the best possible or highest parameter values improve system performance much more than the worst/lowest cause it to deteriorate as indicated in Figure 7-13.

The consideration of uncertainty through stochastic optimisation has the benefit that it will position the network in such a way that it is best prepared for the possible realisations of the world. While the approach of dividing all uncertain parameters into selected models of a best, worst and expected case is perhaps crude, it has the benefit of taking all uncertain data into account. A stochastic model formulation that hedges against many possible combinations of the uncertain parameters is expected to deliver outcomes that are better positioned with respect to all possible realisations of the world, but it would also be highly resource intensive. For this reason most stochastic analyses focus on a limited set of uncertain parameters, for instance only the effect of different demand growth rates. However, it can be debated whether a thorough analysis of a few parameters is preferable to the approach used here if the uncertainty in a number of other parameters in the model is thereby ignored. This debate, and the possibility of a resolution, is however beyond the scope of this thesis.

7.5.4.1 Feasibility of preferred network performance and structure

The question remains as to what effect the consideration of uncertainty has on the preferred network performance and structure identified in section 7.4.2 and 7.4.3. For the same criteria that were imposed in the deterministic analysis, the following performance is now delivered (a comparison, in brackets, is given against the deterministic results)

- **Profit**: 24.2 million AU\$ (13.5 million AU\$, an improvement of 10.7 million AU\$)
- **Energy savings**: 15 million MJ (0.2 million MJ, an improvement of 14.8 million)
- **Average material efficiency ratio**: 3.3 (no change)

The underlying network structure is shown in Figure 7-14. Overall, the flows are comparable to those of the deterministic case, if slightly lower. Some noticeable changes with respect to structure that have occurred are the increased number of links that have become active. These include

- pallet reuse
- particleboard recycling, which requires the investment in particleboard recycling process
- use of virgin resources for particleboard production

These new flows are small compared to the flow along the links that already existed in the network structure identified by the deterministic analysis. The fact that more material allocation options are being used is a consequence of hedging within the stochastic optimisation. As *this* network considers different realities, it is expected that the network is strategically better positioned than the optimal network structure determined for the expected case. This is therefore the network structure that would be recommended for implementation in order to address the sustainable development issues of wood waste disposal, coal use and forestry resource exploitation. In order to verify this assumption, the response of the network would also have to be evaluated for other probability sets for the "best", "worst" and "expected" cases. This is done in the next section.

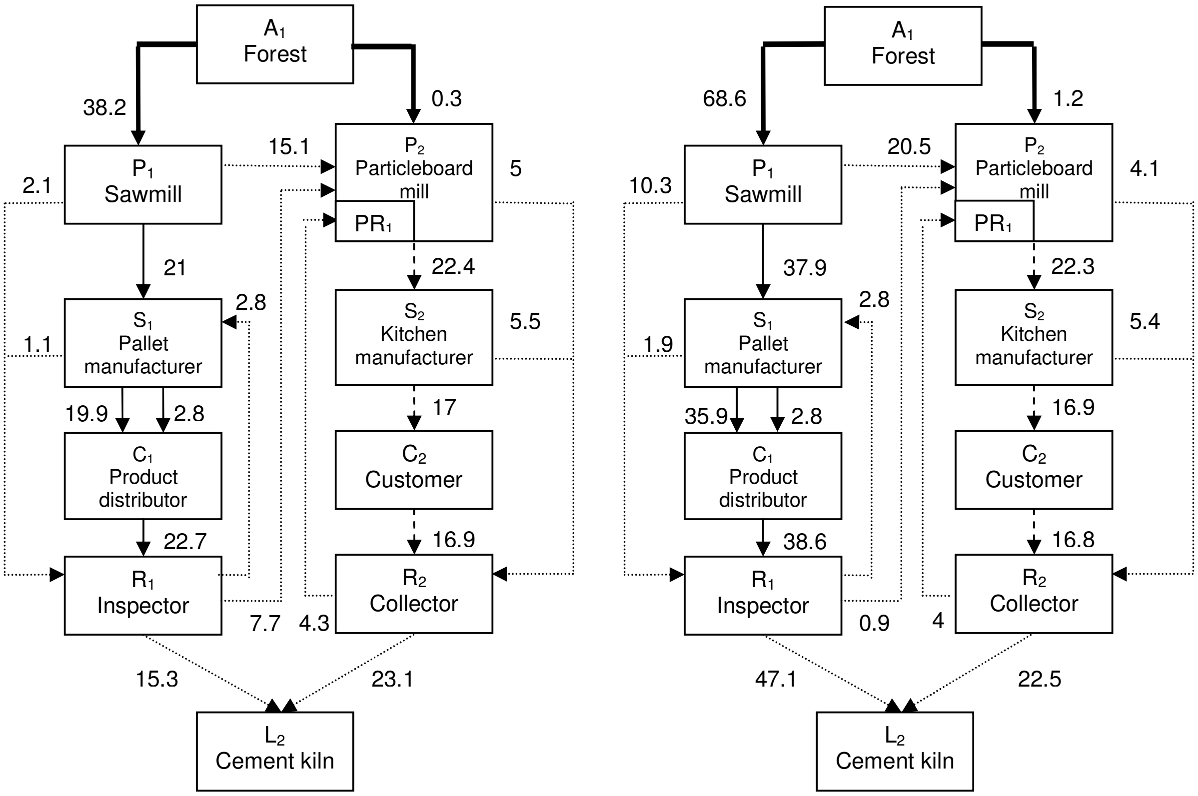

Figure 7-14 Preferred network structure and flows at 24 and 150 months with full consideration of uncertainty

7.5.4.2 Evaluation of model sensitivity to different possible realisations of the world

The above discussion showed that for the stochastic case, where the best, worst and expected realisations of the world had respective probabilities of occurring of 25%, 25% and 50%, the underlying network structure did not deviate substantially from the deterministic evaluation. However, as the probabilities for these three states of the world are rough estimates, the question remains if preferred network performance, as well as structure and development, would differ significantly if the probabilities of the best and worst states of the world being realised would change. Figure 7-15 shows the Pareto surfaces for the expected case, as well as the three stochastic cases. It shows that the stochastic case where all states of the world have an equal chance of occurring (i.e. all having a probability of 33%) delivers similar performance over large ranges to the stochastic case discussed in section 7.5.4.1 (25/25/50). This applies for the energy consumption from -35 million MJ (i.e. excess energy supplied by wood) to 5 MJ consumed, a profit of 27-30 million AU$, and the range of the average material efficiency remains practically the same, from 1-11. The major difference is that the stochastic case where all possible states have the same probability has a much larger range of best possible performance with respect to profit and energy consumption, possibly because it puts greater emphasis on the extreme best and worst realisations of the world. For instance, the case "25/25/50" has an anticipated energy consumption ranging from -32 to 3 million MJ (35 million MJ), whereas case "33/33/33" ranges from -43 to about 17 million MJ (a range of 60 million MJ). The case where the worst and best cases have equal probabilities of 10% of occurring (10/10/80) delivers similar performance than the deterministic case, which is unsurprising in light of the fact that the expected case has the highest probability of occurring.

In section 7.4.2 the preferred state was declared to have a minimum energy consumption of 0 or else an energy provision and a material efficiency of at least 3.3. The striped shading in Figure 7-15 indicates the regions that were thereby excluded when searching for a single preferred state. The coloured boxes with the dotted lines are included to show the sections of the Pareto curves for each case that are still viable under these constraints.

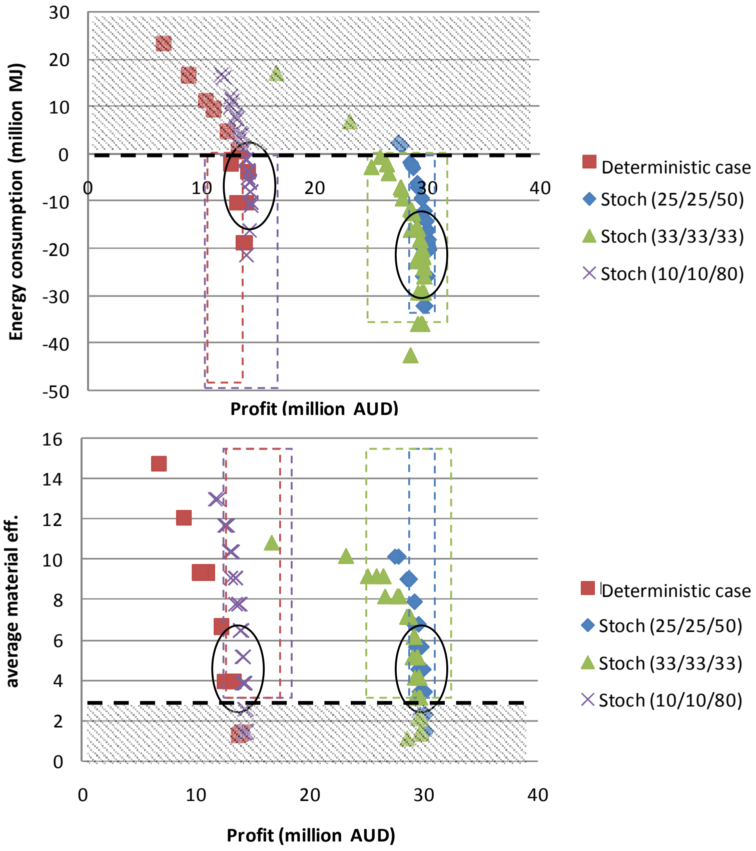

Figure 7-15 Pareto surfaces for the different realisations of uncertainty (Note: The values in brackets represent the probabilities of the best/worts/expected cases in percent)

It can be seen that the Pareto curves overlap in the deterministic and the 10/10/80 case, and in the 33/33/33 and 25/25/50 cases. If one were to follow the same procedure to identify the preferred state within these restricted regions as in section 7.4.3 and 7.5.4.1, the next step would be to maximise profit. A maximisation of profit within these constraints would mean that points are chosen that are situated as far as possible to the right along the x-axis. As a result, energy consumption would be in the region of -10 million MJ for the deterministic and 10/10/80 case, or -20 million MJ in the 33/33/33 and 25/25/50 cases. For all scenarios, maximisation of profit would move the preferred solution down to the constraint of 3.3 for the material efficiency (circled areas in Figure 7-15). As can be seen, the performance of the 10/10/80 case within this region is comparable to the expected case, therefore the network development and structure is expected to be similar as well. Similarly, the performance is not greatly different between the cases 33/33/33 and 25/25/50, and hence structures and development of the network are not anticipated to differ substantially.

Generating full stochastic Pareto surfaces for different probability distributions provides insight into the range of possible network performance under uncertainty. Overall, it also shows the likelihood of network performance falling within the acceptable performance range, i.e. that performance that lies within the chosen constraints. In this case the greater part of the stochastic Pareto curves lies in the acceptable range: The stochastic Pareto surfaces show higher profit than the deterministic case, good material efficiency, and more energy saving, hence the reintegration is likely to improve performance even under uncertainty. The network structure and performance identified in 7.5.4.1 has a good chance of delivering good performance even if material allocation and flows have to be adjusted.

7.6 CONCLUSIONS

The aim of this case study was to demonstrate the ability of industrial network analysis to improve performance with respect to sustainable development in an *existing network*. The case study results show that industrial network performance can be improved with respect to several relevant sustainable development objectives compared to the existing situation when implementing an environmental strategy, in this case reintegration. Even though the network structures delivering optimal performance with respect to each objective differed, in this case performance could be improved in all objectives compared to the base case through the determination of a preferred network structure that traded off between the various objectives.

The key insight of this chapter is the following: The systematic application of the methodology, the information structuring as well as the single objective optimisation, MOO, the identification of preferred performance on the Pareto surface and the uncertainty analysis, have the additional advantage that they provide modellers and decision-makers with a wealth of information about network behaviour, such as how network structure influences network performance and what parameters are the most important. Throughout these analysis steps, from single objective optimisation to MOO under uncertainty, the complexity of the analysis increases. Simultaneously, and with each step, additional insights into network behaviour are provided. For instance, single objective optimisation shows how the optimal network performs with regards to one objective. Under MOO it is shown how this is affected when additional objectives are considered, and to what extent good performance in the original objective can be maintained, or otherwise has to be sacrificed - and to what extent the underlying network structure would have to change to back off from the original optimum. The inclusion of uncertainty, finally, again increases scope to consider how the network is best positioned with respect to not only multiple objectives, but also multiple possible states and futures of the world. While it would be possible to "fast forward" the analysis and immediately enter a stochastic MOO, this would likely provide an amount of data that is more difficult to interpret than if the problem is gradually approached in more complexity as suggested in this thesis.

This case study did not include an explicit discussion of stakeholder perspectives. Instead it adopted only the government perspective that wood waste flows to landfill should be minimised. The results of this work could however be used as a persuasive argument for stakeholders to cooperate (in as far as they have control over the network nodes). Stakeholder input could be neglected here as the analysis is theoretical and aimed to demonstrate the approach, however, for more realistic analysis, and especially if any form of practical implementation is to follow, stakeholders will have to be involved. This would be necessary firstly to get their input about additional options to consider, barriers that may have been overlooked, perspectives on the issue and the strategy, and secondly to try to build consensus and ensure cooperation.

In the next chapter the methodology will be applied in a case study of a bio-energy network. This case study differs from the wood products case study with respect to geographical, political, economic and social context, but also with respect to the facilities and material and product properties. Also, the following case study is one of network design, in that the bio-energy network does not currently exist. As a result, the approach to drawing the network boundary and choice of structure will be less clear and a greater consideration of the network environment is required if feasibility is to be ensured as far as possible. The influence of uncertainty is expected to be greater than in the wood processing case study, to the fact that judgments will have to be made about the location of new facilities, the technologies they use and the operation of these technologies can only be estimated.

8

CASE STUDY 2: CREATION OF A BAGASSE-ENERGY NETWORK

8.1 INTRODUCTION

In the previous case study the focus was on improving performance, with regards to sustainable development objectives, in an established industrial network already operating successfully: the products have a market and the technologies and capacities of the facilities are known. Improvement in network performance was therefore constrained in the extent the strategies of dematerialisation, substitution, reintegration or waste management can be implemented. This second case study addresses the design and analysis of an industrial network that is *not yet formed*. All that exists is a resource and a potential market, as well as competition for both the resource and the market. This raises the question of how the resource is best used, i.e. what products to deliver and what technologies to use to make these products.

The network in this second case study deals with the provision of energy in South Africa (SA). This case study explores the potential for using bio-energy as part of a national renewable energy (RE) strategy. It therefore addresses the issue of non-renewable resource use, and does this by substituting coal-based power through reintegrating biomass waste streams and investment in more efficient technology. Energy provision includes both the delivery of power and fuels. Power provision in general is a topical issue in South Africa due to looming power shortages and sluggish progress in the electrification of rural areas

(DME, 2007c). This has led to the development of an energy security master plan (DME, 2007b). Proposed interventions include accelerated demand side management (DSM), transmission expansion, universal access to electricity (for households, schools and clinics) through regional electricity distributors (REDS) and the introduction of independent power producers (IPPs). This last has proved particularly challenging as South Africa's base price of electricity remains one of the (if not the) cheapest in the world.

The interest of the SA government in providing renewable fuels is demonstrated by the bio-fuels industrial strategy (DME, 2007a). This document states a target of 2% market penetration for renewable transport fuels over the next 5 years.

A number of sources of renewable energy are currently being evaluated by the SA government, such as solar, wind, hydro and biomass (DME, 2003a, b). Of these, only biomass has the potential to serve as a renewable resource for both power as well as liquid fuels. Of all biomass resources in SA, bagasse, the fibrous residue that remains after the sugar containing liquid has been extracted from sugar cane, appears to be one of the most attractive. It is a significant resource in SA, with 16.4 million tonnes cane harvested in 2003 (DME, 2004b). From an environmental perspective, the use of bagasse to generate energy products addresses the issues of waste generation as well as non-renewable resource consumption: Coal and oil can be substituted by biomass-based power and cellulosic ethanol. A further benefit to using bagasse for this purpose is that bagasse would otherwise be treated as a waste. Only a fraction of it is otherwise needed to raise steam for use in the sugar mills. This case study therefore explores the environmental strategies of non-renewable resource substitution and waste reintegration.

The analysis of the bagasse-based RE network is also of interest as it explores a number of industrial network characteristics: Competing uses for the resource are considered, as well as the fact that the product, energy, in turn will have to compete with other pathways that can generate it, such as coal-based power. In the case of this particular network, the socio-political environment also plays a significant role in influencing network objectives and choice of network boundary.

This makes it possible to explore the influences this environment has on choice of generating options, the choice of objectives and consequently on resource allocation.

The purpose of this case study is to

- demonstrate the use of industrial network analysis in designing a new network through the addition of new infrastructure and new facilities as well as linkage to existing facilities.
- determine optimal allocation of the bagasse resource within the network, subject to sustainable development objectives.
- illustrate how to capture the socio-political environment and the effect the consideration of the environmental has on the industrial network analysis.

It differs with respect to the wood products case study in

- the extent to which the network is formed and hence the degree to which the implementation of sustainable development strategies is constrained,
- the properties of the products (energy, as opposed to material),
- the geographical and political context,
- the recycling options available,
- the underlying uncertainties.

The following section provides more detail about the particulars of the case study.

8.2 CASE STUDY BACKGROUND: POWER GENERATION AND RURAL DEVELOPMENT IN SOUTH AFRICA

The generation of RE from bagasse is of interest for three reasons: Firstly, the SA economy relies primarily on fossil fuels (approximately 90%), of which about 75% is coal (DME, 1999). In 1999, 91% of the electricity generated came from coal based power (NER, 2000). Coal combustion is the dominant contributor to SA's greenhouse gas emissions and SA has some of the highest per capita emission of CO2, ranking 27th of 177 countries and therefore comparable to European countries (UNDP, 2008). As a non-Annex 1 country, SA is currently not obligated to meet emissions targets according to the Kyoto Protocol, but this may change after 2012 when the current commitment period ends. Nevertheless the SA government is interested in finding alternative energy generation resources. The fact that renewable energy projects may attract investments as part of Clean Development Mechanism (CDM) presents just one added incentive. This intent was raised in the 2003 *White Paper on Renewable Energy* (DME, 2003). However, the desire to increase the proportion of renewable energy is not limited to power generation, but extends to fuels such as ethanol and biodiesel (DME, 2007a).

Secondly, SA has now reached the limits of its existing generation capacity, with numerous power outages in 2006/07 being the result. A large coal fired power plant has a lead time of five years to build; this could rise to seven years especially if a new coal mine is part of the overall project. Compared to that, a RE power plant takes approximately three years, with distributed generation having an even shorter lead time (EIA, 2001). Bagasse is only capable of meeting a small part of the total projected South African power demand, but could make a significant contribution to meeting the renewable power target. In an effort to accommodate the issues of diminishing resources, energy security and mounting environmental concern, the SA government is interested in strategically diversifying its energy sources to include cleaner technologies (DME, 2003). The government has thus set itself a RE target that, by 2013, an amount of

10,000 GWh per annum is to be provided by renewables, including wind, solar, waste and hydro in addition to biomass (DME, 2003).

Thirdly, large rural regions remain unelectrified in SA. Many rural populations are situated in remote areas far removed form the national grid. This is an obstacle to electricity provision and, as a result, rural communities rely on alternative sources of energy, such as paraffin and fuelwood. Currently 9% of energy use in SA is in the form of fuelwood, which is burned for heating and cooking by the rural poor. However, fuelwood is being over-harvested, and the practice of wood gathering can take up to 10-12 hours per day by members of each household. Added to that social cost, wood smoke and paraffin fumes are a major contributor to infant mortality and respiratory diseases. A further driver for rural electrification is the realisation that electrification is an important foundation for socio-economic upliftment and rural development. To address these issues the Reconstruction and Development Programme (RDP)[31] was initiated by the SA government. The RDP is an electrification initiative aiming to electrify 2.5 million households over the period from 1994-1999. This target was not achieved, and the effort continues, with a total of R1,4 billion allocated in the 2007/8 financial year for the electrification of 150 000 households, 700 schools and all primary health-care clinics, and the building of 10 substations (DME, 2007c). While the target was exceeded, the success was predominately constrained to urban areas, as these areas were easier to reach and cheaper to connect. As a result, by 2000 80% of urban households were electrified, compared to only 46% in rural areas (NER, 2000). Efforts to promote rural electrification continue. Since 1999 a coordinated implementation of non-grid electrification has started to be put in place, with the South African Department of Minerals and Energy (DME) committing approximately 64 million ZAR for non-grid electrification of households from the 2001 fiscal budget to serve as subsidies for the National Electrification Programme (NEP) (Chris and Nyeri, 2001). Furthermore, the National Electrification Co-ordination Committee (NECC) was established, whose main objective is to integrate electrification with other development initiatives in order to maximize benefits to the community.

A further point that has to be considered is the SA government is in the process of deregulating the SA power. This should encourage new players to enter the power market and thereby increase competition with Eskom, the SA power utility (DME, 2007b).

8.2.1 Bagasse as a Renewable Energy Resource

As part of its research into renewable sources of energy, the DME found that among biomass, bagasse from sugar mills is the most attractive resource (DME, 2004a). The main sugarcane areas in SA are

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[31] White Paper on Reconstruction and Development - Government's Strategy for Fundamental Transformation, 1994, http://www.anc.org.za/ancdocs/policy/white.html#PREAMBLE

located in the south-eastern provinces of the country, specifically the KwaZulu Natal (KZN) coastlands and the Mpumalanga lowveld (Figure 8-1). It is a waste product, which means it is cheap, and it is available in significant quantities: in 2003/2004 roughly 6.14 million tons of bagasse were produced, with an embodied energy estimated at 12.12 TWh (DME, 2004a). It is also centrally located at the sugar mills, unlike other biomass like forestry thinnings, thereby costly collection can be avoided. A projected 3,000 GWh a year of electrical energy could come from bagasse[32], which can be increased to 5,500 GWh if field residues like stalks, trash and tops are added (DME, 2004b). However, the collection of this residue is currently not feasible over the large harvesting area concerned. The sugar industry could nevertheless deliver, or help deliver, a significant amount of power.

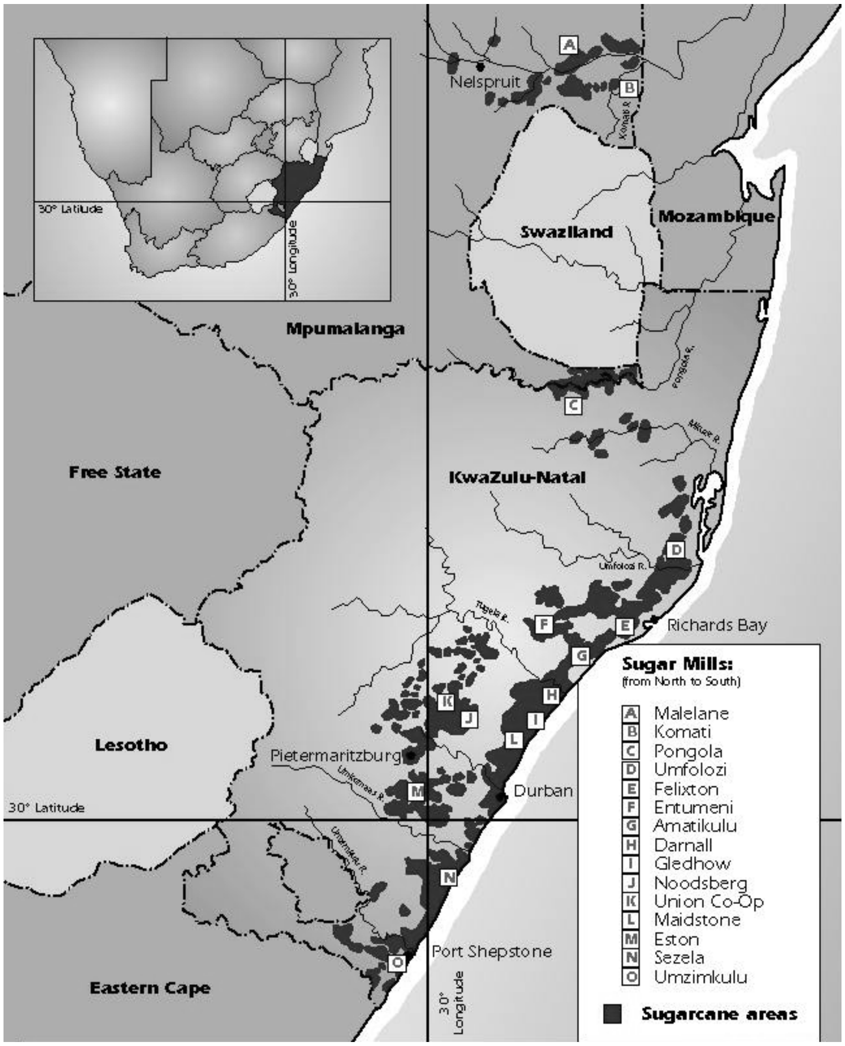

Figure 8-1 Map of South African sugar producing areas. KwaZulu Natal and Mpumalanga are the main sugar producers (SASA, Jan, 2007). (Note: Entumeni mill closed in 2003)

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[32] At 25% net conversion efficiency

Currently, bagasse is burnt onsite at sugar mills to generate heat for in-house steam and power production. The energy content of the bagasse is in excess of the energy needed by the mills. However, to avoid disposal costs, all the bagasse is burned and hence the combustion and use of energy is very inefficient. Compared to normal boilers that can reach energy efficiencies in excess of 80%, the sugar mills run at efficiencies of around 62% (Rasul and Rudolph, 2000). Steam efficiency is around 45% on cane, but could be pushed to 60% if use and generation efficiencies were raised on the plant. Despite this low efficiency it is not uncommon for mills to have 15–25% excess bagasse. It is therefore attractive for the sugar industry, which is dominated by two major companies, Tongaat-Hulett and Illovo Sugar, to find alternative uses for its bagasse. Some mills have succeeded in finding alternative markets for their bagasse, such as selling it for pulp and paper and furfural production, but demand for bagasse for these products is limited. Furfural is used predominately as a selective extractive solvent in the petroleum industry. By selling excess bagasse, or by producing value added products from bagasse, such as power or ethanol, which is becoming more and more popular in the face of rising oil process, the sugar milling companies can create another source of income, provided this move is cost effective.

The remote location of the sugar mills is also attractive from a rural electrification perspective. If the bagasse is converted to power in these remote regions, possibly by the mills themselves, the power can be supplied to the nearby rural population through the use of mini-grids. Furthermore, energy generation from bagasse at the sugar mills would have the additional benefit that energy generation from bagasse would create additional jobs (Siemons, 2001).

Bagasse has also been considered as a supplementary feed with coal at power stations or at Fischer-Tropsch plants for the purpose of gasoline and diesel production. Two issues with using bagasse for large scale power generation or fuel production are its tendency to decompose when stored, and the cost to transport large amounts of the low bulk density bagasse. The latter is the major reason cited why co-firing of bagasse at existing facilities has not been implemented[33]. While drying and pelletisation of the bagasse can overcome this problem, it would require additional investment.

Apart from heat and power production, bagasse has also been considered as a raw material for bio-ethanol since the 1980s (Blanco et al., 1982; Castillo, 1992; Kadam, 2002). Liquid fuels such as ethanol have the advantage that they can be stored and distributed to areas where they are needed. Bio-ethanol has become particularly attractive as an additive to gasoline (Kadam, 2000; Kadam, 2002) and according to the national draft bio-fuels industrial strategy, the target in SA is to achieve a 2% market penetration for transport fuels over the next 5 years (DME, 2007a). Cellulosic ethanol is projected to be much more cost-effective, environmentally beneficial, and to have a greater energy output to input ratio than grain ethanol (Solomon et al., 2007). The generation of bio-fuels derived from cellulosic sources also avoids conflicts

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[33] Personal communication with Brian Tait, SASOL, 12/9/2006

between food and energy production (Hill, 2007). The continuing rise in oil prices is making bio-ethanol production more financially competitive and its use lessens the dependence on imported oil.

Alternatively, ethanol can be converted in a simple process to gel fuel (a solid, wax-like product with good ignition and combustion properties) and substitute paraffin. Paraffin is a cheap, common source of energy for cooking and heating amongst the poor population, however, it is also toxic and explosive. It has been identified as a leading cause for domestic fires, an estimated 46,500 in 2001, and an estimated 60,000 to 80,000 children ingested the toxic liquid in 2004 (Byrd and Rode, 2005; Truran, 2004). Bio-ethanol thus has both health and environmental benefits, and its production could foster the development of locally based industries and employment creation (Tomlinson, 2004).

8.3 APPLICATION OF METHODOLOGY

8.3.1 Problem Definition

The general categories of environmental issues identified in Chapter 2 provide a basis for framing the problem in industrial network analysis: Industry operates unsustainably due to the issues of overexploitation of renewables, use of non-renewables or hazardous substances, low efficiency, waste generation and excessive consumption. In this case study the following environmental issues are to be addressed:

- The inefficient incineration of bagasse and use of the resulting steam, which is predominately a waste disposal exercise providing little economic, social or environmental benefit.
- The adverse environmental impacts of coal-based power use such as non-renewable resource use and global warming.

However, in this case study, it is not only the environmental issue that have to be considered, there are also influences of the network environment which should be considered to ensure that the network structure and development delivered by the industrial network analysis in this case are acceptable. With regards to energy provision in South Africa, there are currently three topical issues that frame the problem context:

- SA faces an energy shortage and needs to identify and implement means to meeting national demand for electricity.
- A renewables' target of 10,000 GWh per annum which has to be met by 2013 has been set in an attempt to reduce greenhouse gas emissions

- The government is interested in promoting rural development through electrification. Failing that, there is a need to providing alternative energy sources to reduce deforestation in poor areas and a cleaner domestic fuel than paraffin to decrease the incidence of respiratory ailments and other public health issues associated with its use.

The problem is clearly not if bagasse should be used, but rather how bagasse use can best serve to meet the environmental issues listed above and those identified by the SA government. The problem statement is captured by the following question: **How is bagasse to be allocated to meet the dual requirements for clean energy and rural development?** In order to answer this question, the opportunities for energy generation from bagasse, the possible markets and competing uses have to be analysed to determine which options are feasible for detailed assessment.

8.3.2 Definition of Network Boundary and Outline of Industrial Network

The environment in which this network is to be embedded has to be considered in detail as it will depend on this environment whether the network is viable, and if it can generate environmental, social and/or economic benefits. The wider network environment includes economic considerations (competitors, prices, markets, regulatory incentives), social considerations (market, work force), as well as the natural environment (existing and anticipated impacts on the environment, as well as geographical and climatic conditions). To determine the bagasse-energy network structure that best meets these objectives requires careful consideration of

- the current uses of bagasse, as well as other uses that may compete with power or fuel production,
- the existing energy infrastructure,
- the technologies available for energy generation, their physical characteristics and costs,
- regulations, policies and incentives,
- transport of materials and products, and transmission of power.

The first step in identifying opportunities to implement the strategies of dematerialisation (technological efficiency improvement), coal substitution and bagasse reintegration is to look at the existing structure. The existing infrastructure relevant to the bagasse to energy conversion is shown in Figure 8-2. It shows the current uses of bagasse, as well as the existing energy generators which can either act as receivers of bagasse or as competing energy generators. The existing infrastructure encompasses the sugar mills, one coal-based power station in the vicinity, oil and coal-based fuel generators.

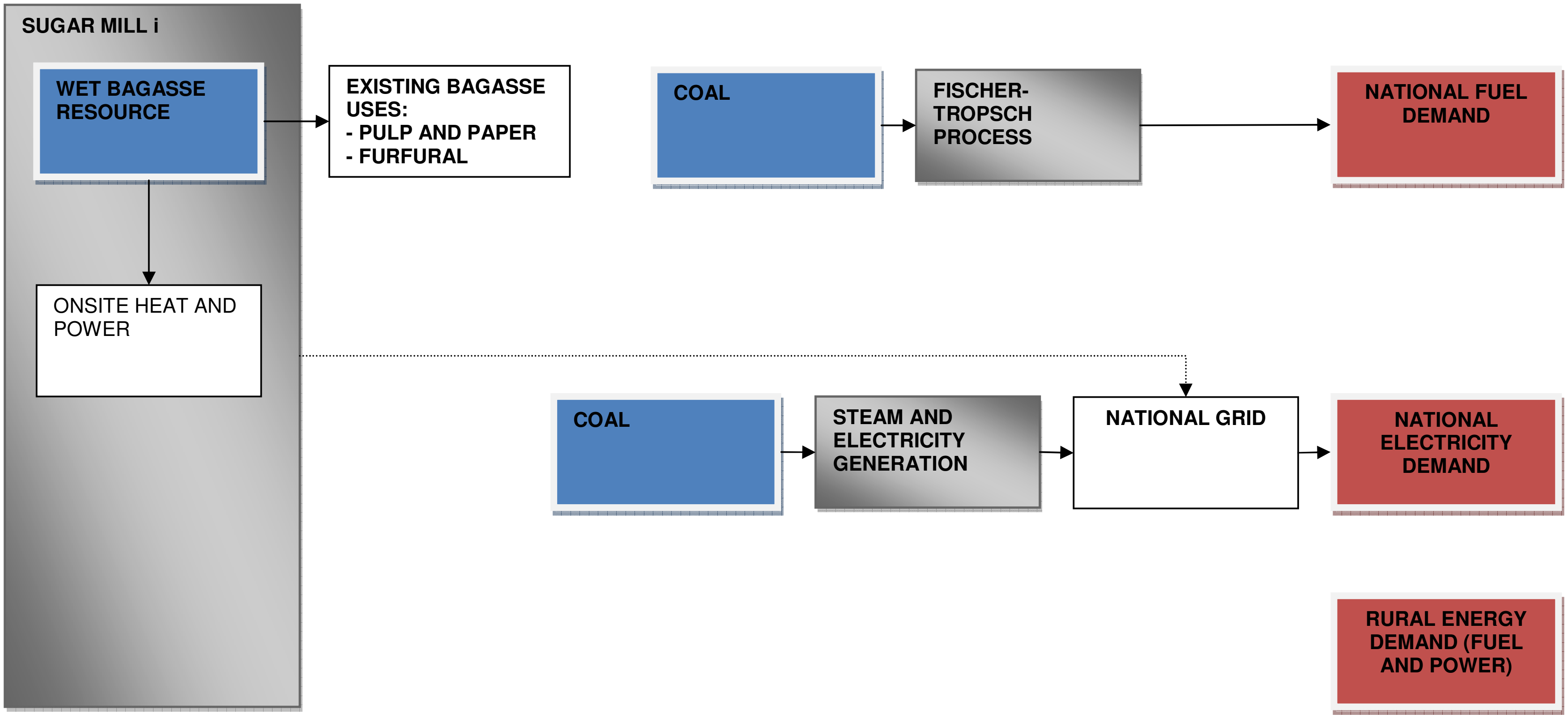

Figure 8-2 Diagram of the existing facilities relevant to the bagasse-energy network. Blue indicates material sources and red product demand.

For the purposes of power and fuel production the following alternatives are therefore included in the analysis:

- the sugar mills as either providers of bagasse or as power generators
- co-firing bagasse in Majuba power station
- the introduction of an independent power producer (IPP).
- the introduction of a bio-ethanol producer for liquid fuel production.

8.3.2.1 Sugar mills

Only the sugar mills in KZN will be considered in this case study as it represents a geographically and administratively distinct area. The majority of SA sugar mills are located in KZN (12 of a total of 14, Figure 8-1) and they have greater proximity to other industries and the grid than the mills in Mpumalanga, the adjacent province. It is assumed that use of bagasse for pulp and furfural production will continue. However, this amount is assumed to remain consistent with the capacity of these paper manufacturing and furfural production facilities. It is assumed that the sugar mills would invest in new power plants, should they decide to become generators, rather than relying on their current boiler systems. The majority of the mills are owned by two large companies, Illovo Sugar Ltd and Tongaat-Hulett Ltd. Illovo Sugar owns five, having just sold one of its mills (KwaDukuza, formerly Gledhow) to Umvoti Transport (Pty) Ltd in March 2005. Tongaat-Hulett controls another four. The remaining two are owned by black economic empowerment (BEE) groups UCL Company Ltd, and Ushukela Milling (Pty) Ltd. The location of these mills is shown in Figure 8-1. The ownership and size of the mills is shown in Table 8-1, as well as any current uses of the bagasse apart from onsite heat and power.

Table 8-1 Ownership and size of mills (DME, 2004b)

OWNER	MILL	CAPACITY 2004 (T CANE)	CURRENT USE OF BAGASSE*
Illovo Sugar Ltd	Maidstone	1 420 000	Electricity
	Noordsberg	1 614 763	
	Pongola	1 426 568	
	Sezela	2 014 283	Furfural
	Umzimkulu	1 136 866	
Tongaat-Hulett Ltd	Amatikulu	1 750 000	Electricity (to grid)
	Darnall	1 350 000	
	Eston	1 307 274	
	Felixton	1 894 726	Electricity, paper
UCL Company Ltd	Union	777 306	
Umvoti Transport (Pty) Ltd	KwaDukuza Mill	1 175 622	Paper
Ushukela Milling (Pty) Ltd	Umfolozi	1 087 606	

* apart from onsite energy demands

The creation of a bagasse-energy network within this environment can take place in a number of ways:

- The mills can invest in more efficient power generation technologies to produce power,
- they can sell their bagasse to an already existing generator or

- new facilities can enter the market, such as power stations or fuel producers.

Currently two of the sugar mills have committed a part of their bagasse to pulp and paper production (Felixton and KwaDukuza) as well as furfural production (Sezela). The furfural is produced on site at the Sezela mill, whereas the paper mills are owned by other companies. Felixton paper mill[34], owned by Mondi, is supplied bagasse by Felixton sugar mill. Sappi's Stanger Mill[35] in turn is supplied by KwaDukuza. While Stanger was recently upgraded, neither Sappi nor Mondi make mention on their website of expanding the bagasse-based paper production. This market is thus not expected to have much potential for growth. Furfural has a small, but growing, international market, however, sales of furfural within SA are low (MacLeod, 2005). The bagasse demand for these applications is therefore assumed to be fixed.

The low price of electricity in SA has proven prohibitive for the sugar mills to enter the energy market, as most forms of renewable energy cannot be generated at similarly low cost. In 2001 the average sales price for electricity was 0.18 ZAR/kWh, ranging from 0.13 ZAR/kWh for manufacturing to 0.27 ZAR/kWh for domestic use (National Treasury, 2004). Nevertheless, small generating facilities totalling 72 MW were installed at 3 mills, Maidstone, Amatikulu and Felixton. Of these, only Amatikulu is connected to the grid, exporting 8.5 MW (DME – Danida, 2005). Amatola Green Power[36], a black economic empowerment (BEE) company launched April 2005, sells the electricity as a prestige product to select customers at an elevated price. Evidently there is at least a small market for green energy as a prestige product. For large scale production as well as rural electrification, government incentives will likely be required.

One issue that has to be considered is that bagasse availability is seasonal. Most sugar mills start harvesting cane March or April, reach peak production around July and finish in November or December (DME, 2004a), with no bagasse available for about 3 months of the year. This situation means that a potential bagasse-reliant generator would lack raw material for a quarter of the year. There are a number of options for dealing with this: generators can substitute bagasse in the off season for other fuel, they can dry and store bagasse throughout the harvesting season and then use the accumulated stocks in the off season, or they can shut down operation from December to March. To retain the focus on bagasse, the option of substituting with another fuel is not include here.

8.3.2.2 Majuba Power station

The most viable option for co-firing is Eskom's Majuba power station, which is closest to the sugar growing area, being just across the northern border of KZN. It is estimated that 5-10% of total feed to the

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[34] http://www.mpsa.co.za/products/flute.htm
[35] http://www.sappi.com/SappiWeb/About+Sappi/Sappi+Fine+Paper+South+Africa/Stanger+Mill.htm
[36] www.amatolagreenpower.co.za

4.1 GW power station can be substituted with either wet or dry bagasse without it adversely affecting process performance or down-stream equipment through slagging or due to high moisture content[37]. The only investment required would be storage and loading equipment. A further advantage is that the power station will be unaffected by the seasonal variability of bagasse supply, as it is otherwise entirely reliant on coal. The disadvantage is the distance from the sugar mills: average distance is about 500 km and the transport effects may therefore play a critical role in determining the viability of this alternative.

8.3.2.3 Potential new infrastructure

The introduction of entirely new facilities dedicated to converting bagasse to either power or fuel is also of interest to the SA government, which would like to see more competition in the SA power market, where Eskom currently holds a monopoly position. For this purpose two types of large scale facilities will be included in the model and their feasibility and performance evaluated: an IPP and a bio-ethanol plant. Durban is seen as a suitable location for these potential new facilities, as it is a major centre close to potential markets and within a reasonable distance of most of the sugar mills in the south eastern part of KZN.

While not fully cost effective now, bio-ethanol production may become so through learning, which means that the technology becomes cheaper and more efficient as the technology becomes more widely used and equipment is manufactured on a larger scale. Two potential markets for ethanol were identified in section 8.2: The ethanol can be either blended with gasoline, thereby substituting fossil fuel, or it can be converted to gel fuel, thereby substituting paraffin as a cooking fuel. The rising price of petrol makes the former economically more attractive, while the avoidance of paraffin stove explosions and subsequent property damage and burns, make gel fuel an attractive product. Another reason why gel fuel would be attractive is that cooking and heating represent about two thirds of the energy demand of rural households (based on census data (Statistics South Africa, 2003)). Hence demand for power, and the underlying required infrastructure, could be reduced significantly if a cheap clean and convenient fuel were available.

8.3.2.4 Technologies

A variety of technologies are capable for converting bagasse into useful fuels and power. For power generation at the sugar mills and IPP, combustion and gasification are particularly appealing (McKendry, 2002a; Mitchell et al., 1995). Bio-ethanol production from cellulosic material like bagasse requires hydrolysis, to break down the cellulosic material into fermentable sugars, coupled with fermentation (see, e.g. Cheng et al. (2008) and Sarrouh et al. (2007)). Another important technology is pelletisation. Drying

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[37] Personal communication with Brian Tait, 12.9.2006. While these figures were quoted for Sasol's Fisher Tropsch process, it is assumed that they are valid for power generation as well.

and pelletising have the dual advantage of reducing bagasse moisture and increasing bulk density. Pelletising thereby enables bagasse to be stored, increases the energy value of the bagasse and reduces the cost of transport. These technologies are discussed here in detail.

Combustion for power generation at the sugar mills and the IPP: During the combustion process, bagasse would be incinerated in high pressure boilers, generating steam to drive a turbine to generate the electricity. Combustion is seen as an attractive option due to its low costs compared to newer technologies and its robustness in regards to feed quality (DME, 2004a). Efficiencies for combustion-based power tend to be in the range between 30 and 40% (Bridgwater et al., 2002; Mitchell et al., 1995).

Gasification for power generation at the sugar mills and the IPP: Gasification, especially when used in form of BIG/GT-CC (biomass integrated gasifier/gas turbine-combined cycle), is becoming increasingly attractive as the technology matures (Bridgwater, 1995; Faaij et al., 1997; McKendry, 2002b; Williams and Larson, 1996), though some issues still require further research, such as tars and ammonia removal from syngas to prevent damage of downstream equipment (e.g. (Juutilainen et al., 2006; Nordgreen et al., 2006) and quick and reliable feed of heterogeneous fuel (Maxwell et al., 2005). During the gasification process, bagasse is burned in an oxygen-deficient environment, creating a syngas, which is a mixture of mainly hydrogen, carbon monoxide, carbon dioxide and water. This is sent to a gas turbine. The gasification technology reaches a high degree of efficiency by using the syngas, which, at a temperature of some 450 to 650°C, is still hot enough to generate steam to drive a steam turbine. The now cool syngas can then be burned to completion in a heat recovery steam generator (HRSG), and the heat being used to in the steam generation plant. This integrated cycle allows electrical efficiencies as high as 79% (at 35 wt% moisture content) to be achieved. (De Filippis et al., 2004). The major draw back of gasification is the higher capital and operating costs compared to combustion. (See Appendix E.1 for a detailed cost break down comparing combustion and gasification costs).

Pelletising at the sugar mills to enable storage, and facilitate transport: Lignocellulosic materials, such as bagasse, have a low bulk density. This causes the transport, storage and handling of these materials to become more difficult and expensive (LAMNET, 2001). In the case of bagasse, an added problem is its high moisture content, which impacts on energy recovered during combustion. By drying and pelletising bagasse, these difficulties can be overcome: Transportation becomes more economical, due to the increased density and easier handling. Drying can raise the power generation efficiency of burning bagasse by as much as 4% net (De Filippis et al., 2004). Finally, dried bagasse can be stored over longer periods of time without decomposing. This is particularly useful as power plants would be able to store bagasse and continue generating during the off-season when no sugarcane is harvested (Erlich et al., 2005). 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).

Recent developments in pelletising have resulted in processes that do not require additional drying and can process biomass resources up to 35% moisture content, a number easily reached through air drying the bagasse prior to processing. The process operates within a temperature range of 55-60°C, which eliminates the need for cooling. The energy requirement of this process is around 70-100 Wh/kg of product depending on the initial moisture content (LAMNET, 2001). 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/m^3.

Bagasse fermentation for bio-ethanol production: The production of ethanol from bagasse requires an initial hydrolysis step that breaks down the hemicellulose portion of the bagasse into fermentable constituents. Subsequently, the cellulose and hydrolysed hemicellulose is simultaneously hydrolysed and fermented by synergistic action of cellulase and other enzymes (Kadam, 2000). Any non-fermentable fractions can be used by CHP to satisfy internal steam and electricity requirements. The hydrolysis step can either take place in a dilute acid environment with the help of enzymes, or it can be done with acid only. The enzymatic process has the benefit that it has a higher yield (0.3 compared to 0.24 l/kg bagasse) (Kadam, 2000), as well as lower CO_2 emissions (3.88, compared to 5.55 kg/l). Furthermore, recent large scale investments by the US government in the development of enzymes to break down lignocellulose into sugars has led to a thirty-fold decrease in the costs of enzyme technology (Bell and Attfield, 2006). The enzymatic process is therefore chosen for further evaluation in this case study.

Gel fuel production: Ethanol can be converted through a simple process into gel fuel, only requiring the addition of a thickening agent such as methyl hydroxyl propyl cellulose[38]. While it has a similar heating value to paraffin (23 MJ/kg), gel fuel has the benefit that is non-toxic if ingested, non-explosive and does not produce noxious fumes and smoke (Byrd and Rode, 2005). Another benefit is its high viscosity, which prevents it from spreading rapidly if a stove containing the gel fuel is accidentally knocked over. It is nearly three times as expensive as paraffin, costing 12 ZAR/l compared to 4.4 ZAR/l of paraffin but also burns longer (Commission on Sustainable Development, 2007).

Figure 8-3 shows the proposed bagasse-energy network including all the proposed facilities and technology options.

8.3.2.5 Grid connection and rural electrification by mini-grid

There are two options for the sugar mills to distribute power: via the national grid, or through the establishment of a mini-grid. Mini-grids are confined to smaller areas (11x12 mile areas have been covered (Zaininger, 2005)) and, unless they cater to some form of energy intensive industry, the demand for electricity within this geographically restricted area would be easily supplied by a small generator. As

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[38] US patent 20030217504

a result, the installation of mini-grids is only really feasible for sugar mills, as they are distributed, as well as smaller generators. For a large-scale generator it would be more cost effective to connect to the national grid. Costs for national grid connection depend on the location of the plant, the size of the plant and the grid voltage at the connection. However, the costs are relatively small with respect to the total costs for constructing a generator. The investment costs for rural electrification depend highly on the number of connections. Dale (2004) mentions distribution costs of around 395 ZAR/kW. With an average household electricity consumption in KZN of 7.84 MWh/household.year (Statistics South Africa, 2003), this would imply that the connections costs would be around 467 ZAR/connection. In terms of rural electrification by grid, Gaunt (2005) reports values from 3568 ZAR/connection in 1995 to 2622 ZAR/connection in 2001. The costs for establishing an off-grid distribution network are thus considerably lower than distributing electricity from the grid.

8.3.2.6 Temporal boundary and system dynamics

Bagasse availability, electricity demand as well as electricity price, are assumed to grow at a rate of 2.5% annually (DME, 2007a; Surtees, 1997). Transport costs are assumed to increase more rapidly, at a rate of 10% pa, based on the long-term price growth of petrol in South Africa between 1975 and 2000 (DME, 2005). The growth rate for costs of fuel and power and resources and CDM is assumed to be 10% (ECE, 2007). In the case of power being fed to grid, or ethanol used as a petrol additive, it is assumed that all the power and ethanol generated can be assimilated fully into the SA energy market. This means the extent to which power or ethanol/gel is generated is constrained by raw material supply rather than product demand. In the case of *rural* energy supply, the market is much smaller. The energy in the form of power and gel fuel that this smaller regional market can assimilate may therefore possibly be less than can be generated from the available bagasse. If any excess power and ethanol is generated this would have to be fed to the grid, or in the case of ethanol, mixed with gasoline.

The model time frame spans 30 years, which covers the expected life times of newly installed plants. The time increment is one year. While harvesting is measured on a monthly basis, sugarcane yield was averaged out for the fraction of the year that bagasse was available. This means that bagasse flows will be higher if wet bagasse is processed as it has to be used within three quartes of the year, whereas dry bagasse can be distributed over the full year. The consequence is that the bagasse plants will have to invest in larger capacities for lower power yield if wet bagasse is used.

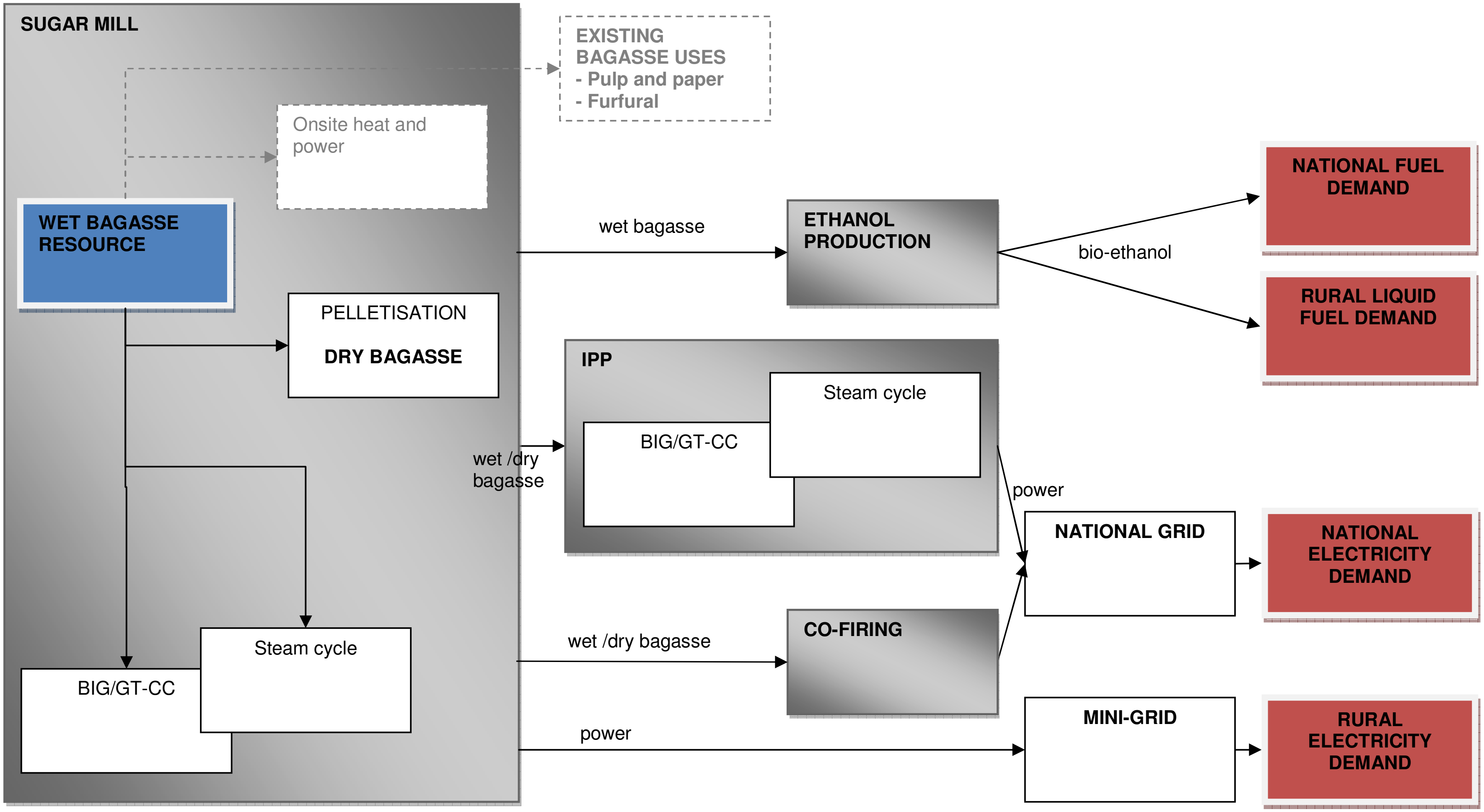

Figure 8-3 Diagram of processing options for converting bagasse to energy. Coal and oil can be substituted through the use of bagasse. Demand of bagasse for paper and furfural production is assumed to be fixed.

8.3.3 Choice of Objectives and Indicators

The aim of this case study analysis is to determine the best allocation of bagasse to satisfy rural energy demand, whilst avoiding the use of coal-based power. To assess the preferred allocation of bagasse, this study will include consideration of the environmental benefit achieved by bagasse use, the social benefit, as well as cost considerations to determine financial feasibility.

8.3.3.1 Environmental benefit: CO_2 emissions averted

During the problem statement a number of reasons were listed why bagasse use for energy products was attractive from an environmental perspective. Firstly coal and oil could be substituted, thereby *minimising the amount of non-renewables* used. Secondly, there is a desire to *minimise the CO_2 emissions* associated with the use of fossil fuels. This translates to a *maximisation of RE* produced. Lastly, by making bagasse a resource with value, the sugar mills have incentive to invest in efficient technology and producing green energy rather than wasting heat energy as is currently the case. There consequently exists the opportunity to *minimise waste* (bagasse). Upon closer examination it becomes apparent that all four are achieved by maximising the amount of renewable energy generated. The higher the output of RE, the greater the amount of fossil fuels substituted. To increase the output of RE, the more bagasse will be used, driving the sugar mills to free up as much bagasse as possible for energy generation. The amount of RE is in direct relation to the amount of CO_2 that can be averted. While maximisation of RE is the common link, CO_2 emissions are seen as a preferable indicator to highlight the environmental benefit. This is due to the fact that mitigating CO_2 emissions is seen as critical, not only in SA, but internationally. An added consideration is that financial incentives, such as clean development (CDM) credits, are potentially available on the basis of CO_2 emissions reduced. Transportation requires gasoline and diesel, and, as a result, long distances for bagasse transport are assumed to adversely affect the environmental performance through increased CO_2 emissions. This indicator, similarly to material efficiency indicator in the previous case study, therefore, monitors the effectiveness of the sustainable development strategies of fossil fuel substitution and biomass waste reintegration, if indirectly.

The amount of CO_2 averted by establishing a bagasse-energy network is calculated in the following manner:

$$CE = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{I}\left[etr_{i,j,t} - es_t\right] \tag{8-1}$$

CE - total network CO_2 emissions (t)

$etr_{t,i,j}$ - CO_2 released at time t by transport from facility i to j (t)

$es_{av,t}$ - CO_2 averted at time t through coal/fuel substitution (t)

$i = [1, 2\ldots I]$ - sugar mills

j = [1, 2… J] - power generation alternatives, including sugar mills
t = [1, 2… T] - time step

8.3.3.2 *Social benefit: rural energy provision*

Social benefit is interpreted as the degree to which rural demand for both liquid fuels and electricity is satisfied. The need for fuel and power is seen as distinctly different energy needs: Energy for cooking and space heating is assumed to be covered by gel fuel, whereas electrical power is delivered for lighting and running electrical equipment. Energy demand satisfaction is included to reflect the government’s desire to further rural electrification and to improve the health and safety among the rural poor by providing cleaner fuel. This directly introduces a consideration of the socio-political network environment into the analysis.

The degree to which energy demand is satisfied can be monitored by measuring the degree to which energy demand is met on a regional level, where the regions are assumed in this case to be the same as the municipal administrative regions in KZN. In the case of power supplied via mini-grid, the supply of one such grid is assumed to be restricted to one of these regions due to their limited range. This assumption has the benefit that recent South African Census data is available that provides detailed information about the number of unelectrified households in each of these regions (Statistics South Africa, 2003).

However, it would be beneficial to promote electrification, as well as liquid fuel supply, in regions that currently have very little access to energy, especially as the provision of energy is taken as a vital ingredient in rural development. Therefore, the electrification of regions with a high degree of unelectrified housing is assigned a higher priority than electrifying houses in a better connected region. This is to promote electrification in those areas with the least access to power, i.e. those regions with the greatest need for electricity. This priority is represented through a priority factor based on the fraction of unelectrified housing in a region. The priority factor is normalised so that the region with the highest need subsequently has a priority factor of 1. On the basis of this a score is developed which is calculated as follows:

$$R = \sum_{t=1}^{T} \sum_{r=1}^{R} \left[\alpha_r \left(\frac{\sum_{ir=1}^{IR} P_{ir,t}}{Dp_{r,t}} \right) + \beta_r \left(\frac{E_{gel}\, x_{gel,r}}{Dl_{r,t}} \right) \right] \qquad 8\text{-}2$$

R	- rural energy satisfaction score for network	(-)
α_r	- priority factor of region *r* (electricity demand)	(-)
β_r	- priority factor of region *r* (liquid fuel demand)	(-)
$Dp_{,r,t}$	- power demand in region *r* at time *t*	(MWh)
$Dl_{,r,t}$	- fuel demand in region *r* at time *t*	(MWh)
$P_{ir,t}$	- power delivered by mill *ir* in region r at time t	(MWh)
$E_{gel,t}$	- heating value of gel fuel	(MWh/t)

$x_{gel,t}$ - mass flow of gel fuel to region r at time t (t)
$ir = [1, 2\dots IR]$ - sugar mill (power producers) in region r
$r = [1, 2\dots R]$ - regions
$t = [1, 2\dots T]$ - time step

While the resulting number does not have a physical meaning due to the inclusion of the priority factors, the social score aims to maximise energy demand satisfaction in the regions in greatest need of energy. In order to obtain some physical meaning from the social score, the score is normalised. This way, social performance of a given network structure and development pathway can be seen in relation to the highest rural energy demand satisfaction possible.

$$R_n = \frac{\boldsymbol{R}}{\boldsymbol{R_{max}}} \tag{8-3}$$

Data used to calculate the regional priority scores in terms of the regional demand, is supplied in Appendix E. The degree to which the regional demand for fuel and power can be satisfied cannot exceed the yearly demand. The municipal region in KZN and the sugar mills that can satisfy that demand are listed in Table 8-2.

Table 8-2 Location of mills within the districts in KZN, regional priority factors and households needing connections

MUNICIPALITY (region r)	DISTRIBUTED GENERATION BY MILLS	α	β	NEEDED CONNECTIONS (“000 hh)
Ugu District	Sezela, Umzimkulu	0.65	0.63	78.3
UMgungundlovu District	Eston, Noordsberg	0.32	0.14	55.5
Uthukela District	-	0.53	0.61	57.2
Umzinyathi District	Union Co-op	0.95	0.83	68.2
Amajuba District	-	0.34	0.22	26.6
Zululand District	Pongola	0.77	0.63	89.5
Umkhanyakude District	Umfolozi	1	0.18	81.2
Uthungulu District	Amatikulu, Felixton	0.59	0.38	81.3
iLembe District	Maidstone, Darnall, Gledhow (KwaDukuza)	0.63	0.50	61.1
Sisonke District	-	0.8	1.00	46.5
Durban: Ethekwini	-	0.25	0.57	159.4

8.3.3.3 Economic evaluation: net present value

While good social and environmental performance make the creation of a bagasse-energy network more attractive, excessive costs of such a network would invariably cause it to fail. As a result some indication of the costs, or preferably the profitability, of the proposed structural changes is required, i.e. the construction of new facilities and introduction of new technologies. For this purpose, the net present value

(NPV) of network formation was chosen. NPV is used in this case study instead of a simple profitability measure (as was used in Chapter 8) as the majority of infrastructure in this network does not yet exist and would have to be built. NPV is commonly used as to indicate if an individual project will be able to pay off its capital and operational costs and generate a net profit over the estimated project life time. In this case it is used to show if the entire system could garner an economic benefit from the network formation (this would be of interest to policy makers who are intent on the promotion of such an industrial network). The bagasse-energy network creation may constitute multiple projects, such as the upgrade of a sugar mill and the construction of a dedicated power plant. A system NPV would be meaningless for the individual parties within the network, but the focus is on achieving the best performance from a global perspective, i.e. for the network as a whole especially as the construction of a bio-energy network is also driven to a large extent by national policy. This point was already presented in Chapter 5. For this reason all investments, costs and revenues of the system can be theoretically seen as part of an overall network project. In this model, all investment decisions are assumed to occur at time zero.

$$NPV = \sum_{t=1}^{T} \sum_{i=1}^{I} \frac{1}{(1+d_f)^t} \left[(r_{i,t} - c_{i,t})(1-\phi) + rec_{i,t} \right] - \sum_{t=1}^{T} CI \frac{1}{(1+d_f)^t} \qquad \text{8-4}$$

To aid the optimisation, the capital investment *CI* is represented as the Fraction of Total Depreciable Capital, $FTDC_{tt}$, for each year, which means the capital investment is divided by the total number of years. This approach was also used in similar models by Hugo and Pistikopoulos (2005) to determine optimal supply chain network configuration.

$$NPV = \sum_{t=1}^{T} \sum_{i=1}^{I} \frac{1}{(1+d_f)^t} \left[(r_{i,t} - c_{i,t})(1-\phi) + rec_{i,t} - FTDC_t \right] \qquad \text{8-5}$$

$$FTDC_t = \frac{\boldsymbol{CI}}{\boldsymbol{T}} \qquad \text{8-6}$$

NPV	- Net present value for network	(ZAR)
d_f	- discount factor	(-)
$r_{i,t}$	- revenue from sales	(ZAR)
$c_{i,t}$	- operating costs	(ZAR)
$rec_{i,t}$	- salvage value	(ZAR)
ϕ	- tax rate	(-)
$FTDC_t$	- fraction of total depreciable capital	(ZAR)
i = [1, 2… I]	- index representing facilities	
t = [1, 2… T]	- time step	

Where the operating cost $c_{i,t}$ is composed of the cost for raw materials, transport as well as maintenance and operation.

$$c_{i,t} = ctr_{i,j,t} + cmo_{i,t} \qquad 8\text{-}7$$

$ctr_{i,j,t}$ - cost of transport (ZAR/t.km)
$cmo_{i,t}$ - cost of maintenance and operation (ZAR/MWh) or (ZAR/t ethanol)

The discount rate used was 8% (du Preez, 2004), and tax was set at 29%, the South African business tax rate. While the system NPV takes the global view to assess overall attractiveness of creating the industrial network, the economic performance of individual facilities also has to be determined. This can be done by including NPV calculations for each facility in the optimisation that will show the individual facilities" NPV's for the preferred network structure and development identified. Some individual facilities could operate at a loss even if the overall system were profitable. This is a barrier that would have to be overcome if the system were to be implemented. However, if the network delivers beneficial performance with respect to other objectives and the costs are not prohibitively high it may be desirable for the SA government to subsidise the unprofitable facilities.

8.3.4 Choice of Scenarios

Scenario analysis was recommended in Chapter 6 to determine the effect on analysis outcomes of two types of model form uncertainties: future and system uncertainty. These refer to uncertainty in future events in the network or network environment, and uncertainty regarding what is included in the analysis, e.g. choice of indicators, nodes or links. In this case study, scenarios will be used to determine the effect that the inclusion of the following aspects has on network performance:

1) different technology choices
2) different economic policy incentives

Future scenarios are not considered, however the exact same approach would be applied to interrogate the influence of possible future events on analysis outcomes, as is demonstrated here with system uncertainties.

Technologies: The following scenarios are based on the technology options discussed in section 8.3.2. The sugar mills and the IPP are given the option of

1. both generating electricity with gasification ("gg")
2. both generating electricity with combustion ("ss")
3. IPP installing gasification and the mills staying with combustion ("gs")

4. the sugar mills upgrading to gasification and the IPP investing in combustion (“sg”).

In each case the sugar mills have the choice to

a. feed to the national grid, or
b. contributing to a mini-grid

Also, for each of the power generation options (in the cases scenarios 1-4) the effect of pelletisation on the network is investigated.

c. If pelletisation is available
d. If pelletisation is not available
e. If pelletisation is enforced to allow round the year processing

Policies: Furthermore, it is meaningful to consider various policy instruments which could positively influence the profitability of networks which are attractive in terms of their social and environmental benefits. Under consideration are:

a. clean development mechanism (CDM) investments, amounting to 31 ZAR/MWh renewable energy (based on an estimate of 5 US$/t$CO_2$ avoided[39] (IETA, 2005; Spalding-Fecher, 2002)),
b. capital funding in investments that reduce greenhouse gases (up to 30% (DME, 2004a)),
c. a combination of the above incentives.

Hypothetically, all these options could be included in a single model, allowing the optimisation to choose the scenarios that perform best with respect to the different objectives. However, this approach would not supply any information about why the other options were rejected, and how their best performance would compare. For instance, how much more profit/less CO_2/greater social benefit a network provides that makes use of one technology mix over another. As a result it is preferable to divide choices concerning uncertainty about network configuration (system uncertainty) into the discrete scenarios outlined above to enable comparison. The increased amount of information supplied by a range of scenarios also contributes to a better understanding of how the network operates, as well as how and to what extent performance is affected through technology and network linkage choices. Scenario analysis is therefore attractive as it spreads uncertainty over multiple scenarios, making the effect of system boundary and structure choices (and future developments) that much clearer.

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[39] Exchange rate 6.2 ZAR/USD, October 2005.

8.3.5 Model of Bagasse-Energy Network

The facilities (potentially) forming part of the network are categorised according to function in the following manner:

A = [Amatikulu, Darnall, Eston, Felixton, KwaDukuza, Maidstone,
Noordsberg, Pongola, Sezela, Umfolozi, Umzimkulu, Union Co-op] Resource sources 8-8

P = [Pelletisation] Primary processing 8-9

S = [Amatikulu, Darnall, Eston, Felixton, KwaDukuza, Maidstone,
Noordsberg, Pongola, Sezela, Umfolozi, Umzimkulu, Union Co-op, Secondary processing 8-10
IPP, Majuba, bio-ethanol production]

C = [grid, rural energy, fuel] Consumers / markets 8-11

T = [gasification, combustion] Technologies 8-12

The supply chain in this case is reasonably short, shorter than the pallet and particleboard supply chains in the previous case study. This again highlights the influence of material properties on network structure and possible sustainable development strategies. As electricity and fuel are consumed and converted to work and heat, no reintegration options are available.

The material circulating within the network can be classified into four general types.

M = [wet bagasse, dry bagasse, ethanol, gel, electricity] 8-13

The full network structure, which serves as the basis for mass and energy balances (which are provided in Appendix E) is depicted in Figure 8-4 (pp 208).

The capital and operating costs for gasification and combustion plants show economies of scale, meaning that the cost per unit power decreases with increasing plant size and operational load (Bridgwater et al., 2002; Williams and Larson, 1996). The same trend could also be observed in literature data for the energy efficiencies of the combustion and gasification technologies; however, this was moderate and could therefore be replaced with a linear approximation. Economies of scale could also be observed for capital investments for bio-ethanol plants and biomass pelletisation, however, operational costs are linear or independent of plant scale (LAMNET, 2001). A note on the determination of capacity: Unlike in conventional process design, capacities are not chosen *a priori*. Instead, the capacities of the facilities are determined by the optimisation. In the case of NPV maximisation for instance, the capacity would reflect a compromise between higher revenue through greater power output, greater capital and operational costs, as well as the duration that the facility would be unable to run at full capacity due changing availability of bagasse.

Costs associated with co-firing bagasse at Majuba power station are assumed to be small, only involving investment in loading and storage equipment and operational cost of handling the bagasse in addition to the coal. No cost data was available, but capital and operating costs were assumed to be very small compared to the other bagasse processing options, at 150 and 100 ZAR/t, respectively. While the DME recommends a price of 250 ZAR/MWh for RE (DME, 2004b), as the analysis will still show in the next section 8.4.1.1, this price would barely make investments in renewable technologies viable. To promote investment in renewable energy, prices of around 500–600 ZAR/MWh would be more attractive. Prices in this order of magnitude are not unreasonable: Within the EU and Australia, prices for RE range from 500–1,000 ZAR/MWh. Hence, a minimum green electricity price of 500 ZAR/MWh was therefore used.

Each MWh of renewable power was assumed to substitute an equivalent amount of coal based power. Similarly, each ton of bio-ethanol was assumed to substitute an energy equivalent amount of gasoline, or, if processed further into gel fuel, each ton of gel fuel could substitute an energy equivalent amount of paraffin. Each unit of these fossil fuels (coal, gasoline and paraffin) has a specific release of CO_2 related to it. Table 8-3 shows the values that were used to determine the overall amount of CO_2 emitted or averted by the possible network activities.

Table 8-3 The amount CO_2 emitted/averted during network operation (Johnson and Heinen, 2004; Spalding-Fecher, 2002)

CO_2 EMISSIONS	**VALUE**	**UNIT**
Averted for gasoline	0.24	t CO_2/t gasoline
Averted for coal	0.91	t CO_2/t coal
Averted or paraffin	1.561	t CO_2/t paraffin
Emitted during transport	0.017	t CO_2/t.km

For a detailed discussion of literature data, assumptions and network equations, mass and energy balance equations are provided in Appendix E. The models are solved using GAMS/COIN-OR solvers, particularly CoinCbc and CoinGblk[40].

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[40] http://www.coin-or.org

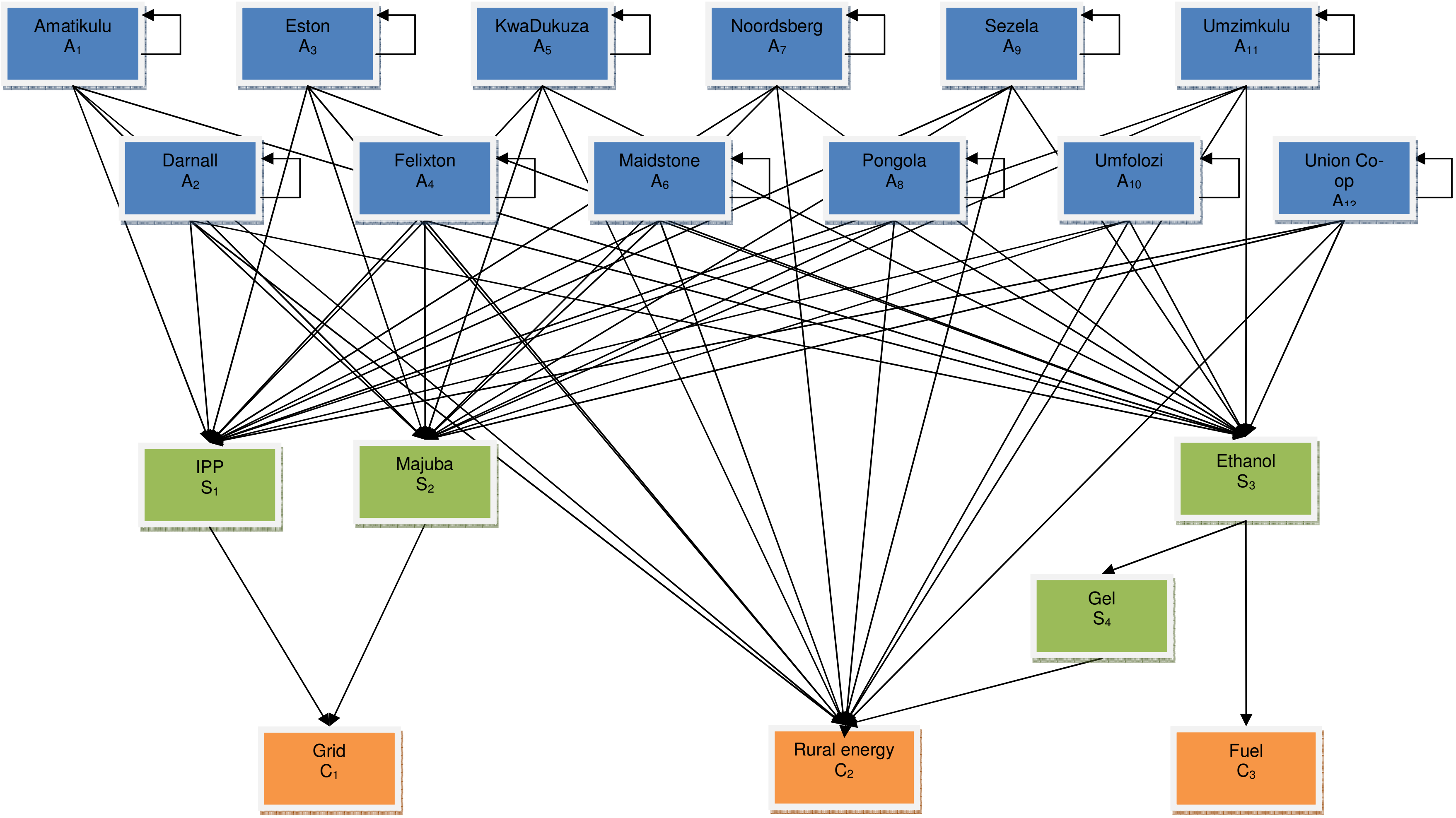


Figure 8-4 Structure of bagasse-energy network

8.4 RESULTS

The quantitative analysis is intended to give an indication of

- how industrial network structure and performance interrelate,
- how the assumptions influence dynamics, i.e. how the network develops and which facilities and capacities are chosen to accommodate the expected time-dependent developments, and
- the influence of valuation and technical uncertainty on the robustness of the proposed preferred network structure and development.

First off, a quick review of the procedure for the generation of results: Initially, network performance is optimised within each scenario with respect to each objective individually. This provides information about how the network structure influences network performance. A network structure that manages to achieve a "good" performance with respect to each objective is then determined through the dynamic multi-objective optimisation and a prioritisation between the objectives. The results of the single objective optimisation are used to help construct Pareto surfaces, which show the trade-offs between the objectives and allow a decision-maker to choose a preferred performance, and an associated network structure, that best satisfies all objectives in accordance with their relative importance (a value judgement on the part of the decision-maker).

8.4.1 Best Network Performance and Structure for Individual Objectives

8.4.1.1 System NPV

The results for the maximisation of NPV are shown in Figure 8-5. Though different technology combinations are provided, only two network structures are adopted by the optimisation: Economic performance is maximised if the IPP adopts gasification technology, achieving a NPV of roughly 16 billion ZAR. In this case the IPP is the main generator, receiving about two thirds of the bagasse and installing a capacity of 1.5 GW. The IPP has the advantage that, due to its much greater capacity it can operate at a higher efficiency than the smaller sugar mills. At the same time, it has the benefit of lower investment per unit of power generated than the smaller mills. This significantly reduces the capital and operating cost. While the capital outlay for the existing power station to co-fire bagasse would be minimal, over the 30 year time frame, this initial benefit is offset by the high transport cost due to the great distances from most of the mills as well as the lower efficiency of the plant. However, if the IPP were to be built using conventional steam cycle technology, then it becomes more attractive to instead send bagasse to co-firing rather than having the IPP generate or the sugar mills investing in power plants. The NPV in this case is significantly lower, only reaching 2 billion ZAR.

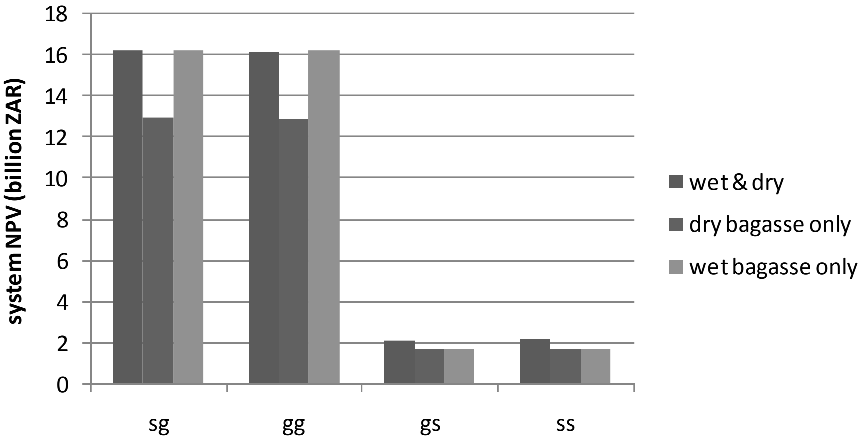
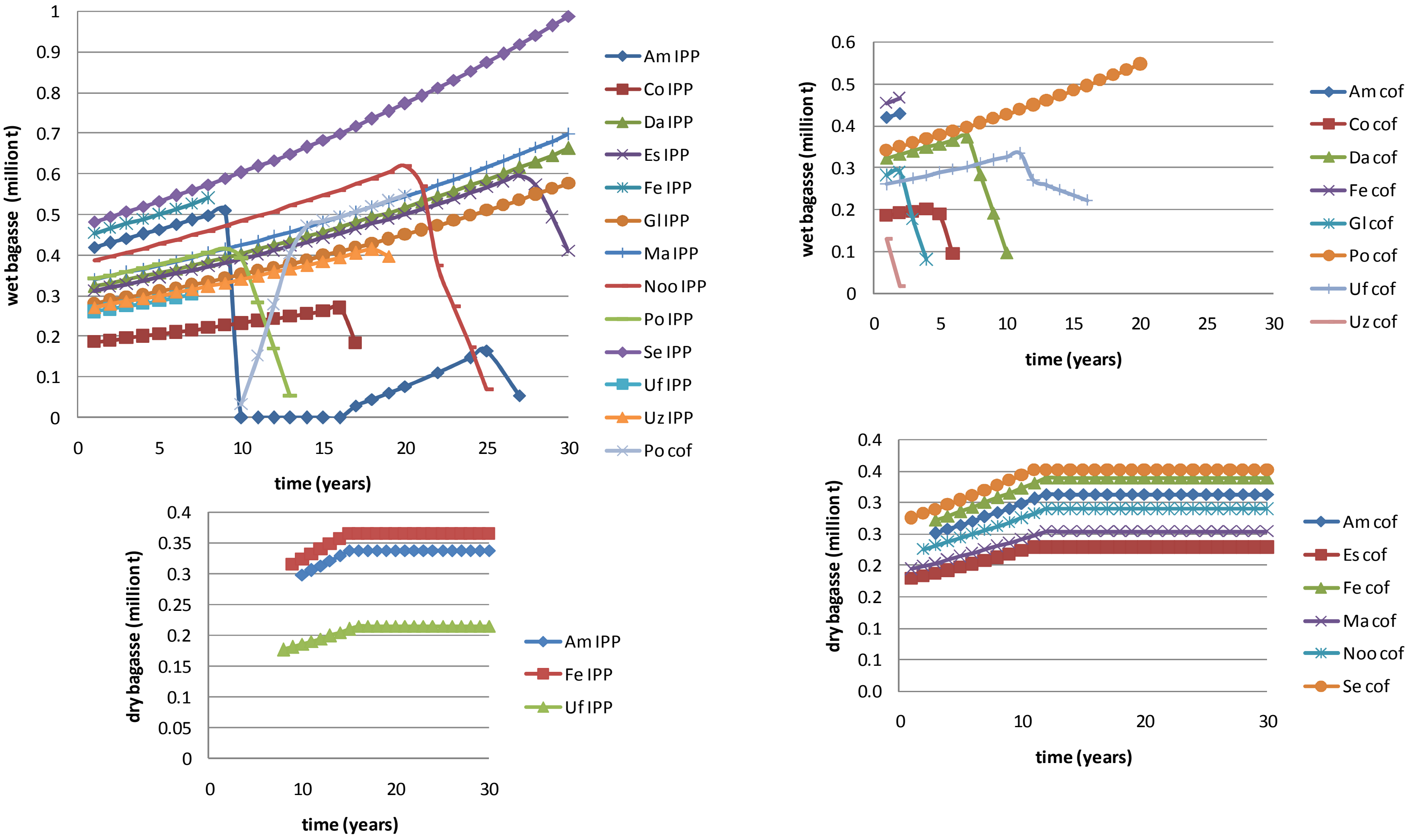


Figure 8-5 Maximum NPV possible for the various network structures (grid connection). Although difficult to see, the optimal combination of wet and dry bagasse achieves a slightly higher NPV.

Due to the decreased cost of transport, and the higher heating value of the product, it would appear that drying and pelletising bagasse are preferable. However, Figure 8-5 shows that, if the IPP is the main generator (sg, gg), to constrain the network to using dry bagasse results in financial losses of nearly 20%, bringing the NPV down to 13 billion ZAR. The use of exclusively wet bagasse has little effect on the best possible economic performance, only lowering NPV by 50 million ZAR. This is due to the added cost of drying, offset by the increased revenue from the added power and reduced transport costs. In the case where the IPP employs only a steam cycle (ss, gs) and where co-firing is seen as preferable, the restriction to use either only wet or only dry bagasse proves equally detrimental lowering NPV from 2.2 to 1.7 billion ZAR. This indicates that when pelletising is not enforced, but merely an option for the sugar mills, a balance is struck between transport costs and the investment and operating cost of pelletisation.

Figure 8-6 shows the flow rates of bagasse over time for the two network structures and developments adopted by the optimisation (for the case where the model is free to chose the respective amounts of wet and dry bagasse used). Results are shown for the case where gasification and combustion are the only technologies used, respectively. While the fixed structure of the network is easy to ascertain, the material flows within this network that yield optimal performance can show quite complex behaviour. For example, looking at scenarios “sg” and “gg” (Figure 8-6 *a)*), all sugar mills send bagasse to the IPP, with the exception of Pongola. Due to this mill’s location in north-eastern KZN, it is the mill that is situated closest to the power station in Mpumalanga. As a result it is viable for this mill to send wet bagasse to Majuba, but only once cane growth, and hence bagasse yield, has risen to the point here Pongola’s bagasse is in excess of what is needed to run the IPP at maximum capacity (after 8 years).



a)

b)

Figure 8-6 Flows of wet and dry bagasse for the network structure with the best NPV: a) for the scenario where gasification is the only technology (same network structure as the scenario using gasification for the IPP and combustion for the mills), b) for the scenario with combustion the only possible technology (identical to the network structure using steam cycle in the IPP and gasification for the sugar mill power plants)

Figure 8-6 a) also shows two other interesting trends: three mills, Amatikulu, Felixton and Umfolozi, stop sending wet bagasse after 8 years and instead substitute this with pelletised bagasse. The pelletisation plants are installed at capacities of 0.34, 0.37 and 0.22 million tons respectively, which they reach after roughly 15 years. By doing this, the mills compensate the IPP for the loss of Pongola's bagasse. As Amatikulu, Felixton and Umfolozi are also furthest from the IPP the decision to pelletise is attributable not only to the loss of Pongola's bagasse, but also to the rapidly rising cost of transport. The other trend in the system is that various mills cease sending bagasse at different points in time: Union Co-op, Umzimkulu, Noordsberg and Eston, drop out consecutively, after 16, 18, 19 and 27 years respectively. This is due to the fact that the continuing cane growth provides bagasse in excess of the IPP's requirements. Hence the mills that are the furthest from the IPP are the first to stop supplying bagasse, thereby reducing transport costs while other mills collectively take over the delivery.

For scenarios "gs" and "ss" (Figure 8-6, *b)*), the only option realised is co-firing of bagasse. Only a limited amount of bagasse can be used this way, as the Majuba power station has a limitation on the amount of bagasse it would co-fire, which means that a maximum of 400 MW only of renewable energy is generated. This means that much less bagasse is used overall, but also that more bagasse has to be pelletised to avoid excessive transport costs. All the biggest mills invest in pelletisation as they can produce dry bagasse pellets cheaper than the smaller mills. The costs associated with pelletisation are still cheaper than the option of having the mills generate, no matter what technology they use, or having the IPP generate power via the steam cycle alone. Similarly to the previous case, a series of mills switch to pelletising once transport costs become too expensive, which in this case is already after 2-4 years, or they drop out altogether as more closely located mills can take over bagasse delivery. The only mill sending only wet bagasse is Pongola, due to its proximity to Majuba, but even this mill stops bagasse delivery after 20 years in favour of other mills delivering pelletised bagasse.

The sort of dynamic behaviour observed in Figure 8-6 illustrates the importance of considering time-dependent developments in the network and its environment, which was pointed out as an important aspect to include in analysis in Chapter 1 and Chapter 3, where dynamic behaviour was discussed as a network characteristic. As a consequence of the dynamic developments, decisions that have to be taken early on in time adapted based on the expected future developments.

Other observations: Figure 8-7 shows the effect that various financial incentives may have on the network performance. CDM credits provide the biggest advantage, followed by capital investments. These raise the profitability of the network without changing the underlying optimal structure. Tax rebates for fuel fail to make ethanol production financially attractive enough for bagasse to be diverted from power production. This is due to the high capital and operational costs currently involved. However, bio-ethanol production from cellulosic sources is experiencing significant growth world wide. It would therefore be likely that the cost of this technology would decrease through learning, i.e. as installed capacity increases, over the coming years. Learning rates of around 20%, i.e. where the cost of a technology becomes 20% cheaper when the installed capacity doubles, have been anticipated for renewable technologies such as wind and photovoltaic energy generation (Haw and Hughes, 2007), though, as bio-energy technology is already more mature, learning rates would be expected to be lower.

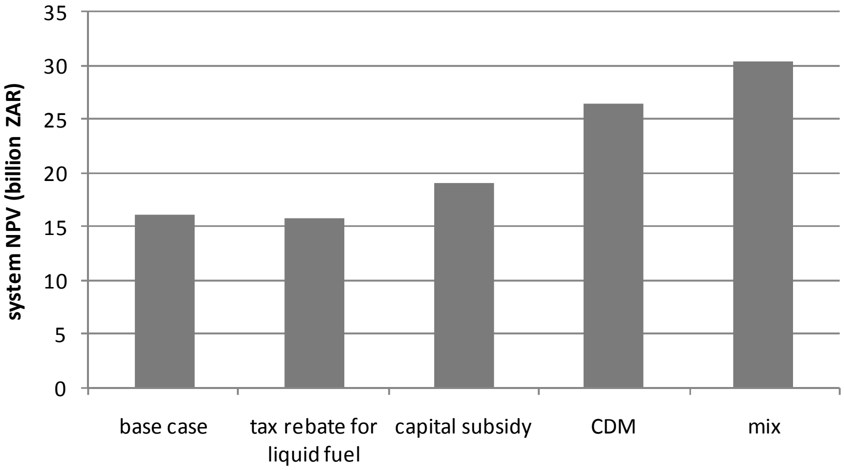


Figure 8-7 Improvement in possible network NPV for a variety of financial incentives.

A sensitivity study showed that under the model assumptions, the network would begin to be profitable when the electricity price rises above 260 ZAR/MWh (Figure 8-8). This is compared to the 250 ZAR/MWh expected by the DME, but naturally the higher the price for green energy, and especially green electricity, the more attractive investments in these technologies become and the more CO_2 can be averted. For rural electrification, the lower price of 260 ZAR/MWh would however be good news, as this would make the power provided from the sugar mills more affordable for the poorer rural population.

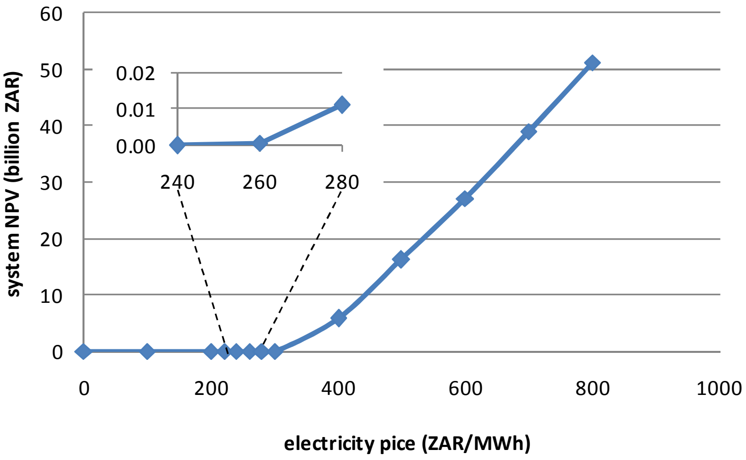


Figure 8-8 Sensitivity study showing effect of electricity price on viability of bio-energy network.

8.4.1.2 CO_2 Emissions

The choices of technologies adopted by the power generators, as well as the choice to use dry or wet bagasse, have a significant influence on the amount of CO_2 emissions averted. Figure 8-9 shows the best environmental performance possible for the various technology combinations, and under different degrees of drying of the available bagasse. Again, two different network structures underlie these performances. The first sees the sugar mills as being the only generators (“gg”, “gs” and “ss”), and the second only involves the IPP (“sg”). The scenarios where the sugar mills install gasification plants (“gg” and “gs”) result in identical and overall best environmental performance, reaching values of 312 million tons of CO_2 averted over the 30 years. The scenario where technology is restricted entirely to combustion has by far the worst performance, with overall CO_2 savings being 20% less than what is otherwise possible. This is due to the lower efficiency of combustion. In scenario “sg”, where the IPP invests in gasification while the mills focus on the less efficient steam-based power, the CO_2 savings would decrease only slightly, by about 10 million tons or 3%.

The use of dry bagasse in each case delivers better performance. Wet bagasse results in less CO_2 being averted (e.g. about 20-35 million tons over the 30 year time frame in those cases where the mills generate (“gg”, “gs” and “ss”)). When the IPP becomes an active player in the network, being restricted to wet bagasse use is much more detrimental, lowering the CO_2 savings by 60 million tons. In addition to the efficiency losses resulting from firing wet bagasse, the CO_2 saving are further lowered by transporting the heavier and less dense wet bagasse.

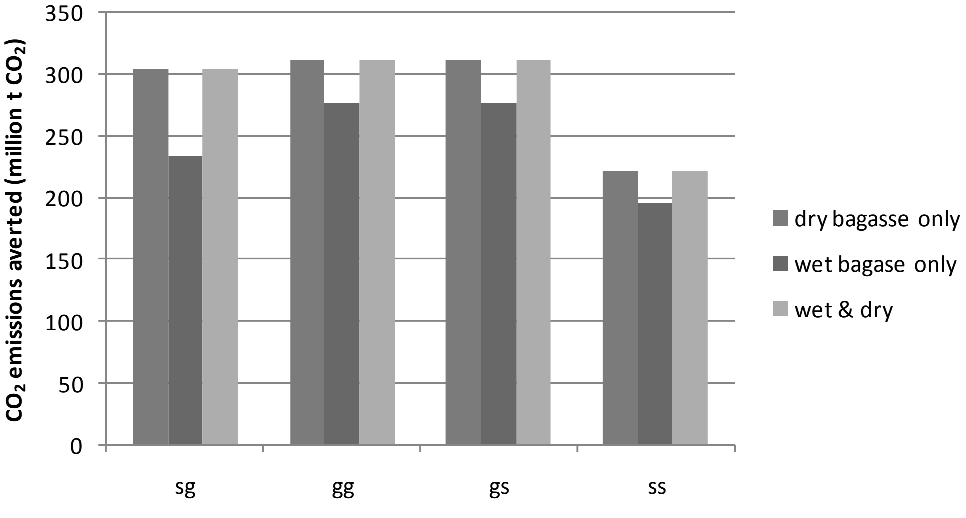


Figure 8-9 Results for minimisation of CO_2 emissions: The optimum is only influenced by the nature o the bagasse used. Dried bagasse creates a higher yield, and hence a greater amount of coal can be substituted.

In those situations where the IPP and the mills would use the same technology (“ss” and “gg”), or where the IPP would install the less efficient combustion (“sg”), the network configuration to minimize emissions involves all sugar mills investing in pelletisation and power generation to the extent that they can utilise all the bagasse they have available each year (Figure 8-10). This avoids transport emissions, while obtaining the maximum power output. The pelletisation process consumes some wet bagasse in order to supply the necessary heat to the drying process, however the remaining dried bagasse now has a higher calorific value due to lower moisture content, and is therefore able to generate more power. Due to higher efficiencies, the IPP would technically be able to generate more power and substitute more coal based power emissions. However, this advantage is offset by the transport emissions. Investments in such a network structure, where the plants, both for power generation and drying, are only operating at capacity in the final year of the build cycle, would however be prohibitively expensive, incurring losses exceeding 100 billion ZAR.

If the sugar mills would only consider using combustion, the IPP could provide better environmental performance with a gasification plant. In this case all available bagasse within the system would go to the IPP instead of the mills, in pelletised form. The flows would be the same as those shown in Figure 8-10, however, in this case the bagasse would be transported from the mills to the IPP. As this scenario again involves operating at a much lower capacity than that of the constructed plants, this option is also not cost effective.

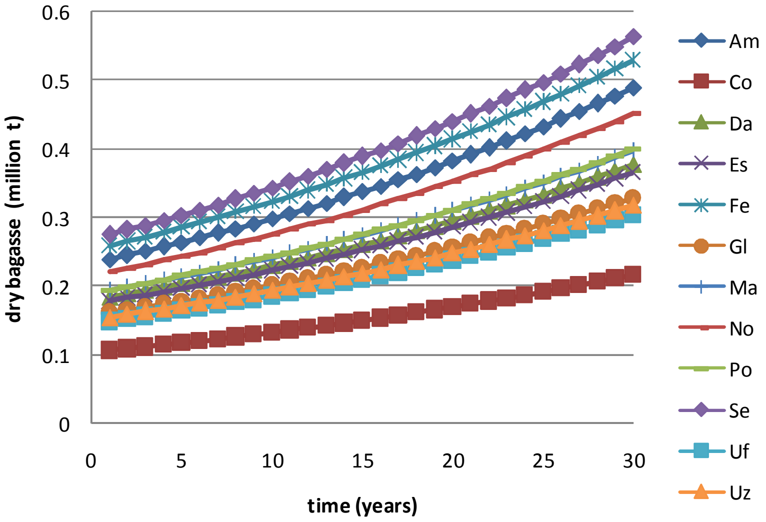


Figure 8-10 Flows of bagasse to achieve biggest aversion of CO_2 emissions

In the scenarios where mini-grids are the only means of distributing their generated power, the mills would not be able to turn all bagasse available into power as indicated by Figure 8-10. This is due to the fact that rural power demand is lower than what the mills could supply. They would consequently have excess bagasse. This would be sent to the IPP, which has the highest conversion efficiency of the remaining facilities, to obtain the maximum amount of power, and hence CO_2 savings. This would deliver somewhat worse performance, as now some of the CO_2 savings are offset by the CO_2 emissions associated with transport of the pelletised bagasse and some power would be lost in transmission, though this is not considered in this model.

8.4.1.3 Rural energy provision

The social benefit of the network is maximised by satisfying rural demand for fuel and power as far as possible. If no mini-grid is constructed, the only means to supply energy is through the delivery of gel fuel to the rural areas or through linkage to the national grid. The latter however proves to be too costly to be competitive with mini-grid (Information on grid cost is provided in Appendix E). Connecting the rural areas to the national grid for power is too expensive to be feasible. The regional demand for liquid fuel can be fully satisfied by converting the bagasse, giving a social score of about 688 (Figure 8-11). The establishment of a mini-grid improves the social score by 20%, to a score of nearly 835. However, as these scores have little physical meaning, only normalised social scores are used for the remainder of this discussion. All social scores are normalised with respect to the highest possible score, 835. With the mini-grid, the sugar mills can provide electricity for rural electrification in seven regions additionally to providing gel fuel to satisfy the demand for heating and cooking fuel. As the available bagasse in the network can produce both power and fuel in excess of regional energy demand, the total demand for energy could be easily satisfied, irrespective of whether the mills use gasification or combustion, or if the network is restricted to wet bagasse use. However, this is only the case if the mills are linked to mini-grids, or if the rural areas were connected to the national grid.

The presence of an excess of bagasse means that there are several network structures possible that allow the social score can reach its maximum value. In other words, once the rural energy demand is satisfied, the excess bagasse can be distributed in different ways amongst the remaining facilities, such as Majuba and the IPP, that do not contribute to rural electrification. This existence of multiple states that deliver optimal performance, i.e. multiple optima, can cause optimisation solvers to jump between states. Some of these optima deliver unrealistic behaviour. While these optima should technically all be considered this would create significant additional computational and analysis effort while not providing much additional insight if most states are dismissed as they are seen as physically unrealistic. To avoid this, the preferred structure to satisfy the rural energy demand is determined by constraining the social score to its maximum value and determining the structure that then has the best NPV. The resulting network configuration is shown in Figure 8-12. This decision was motivated by the importance that costs have

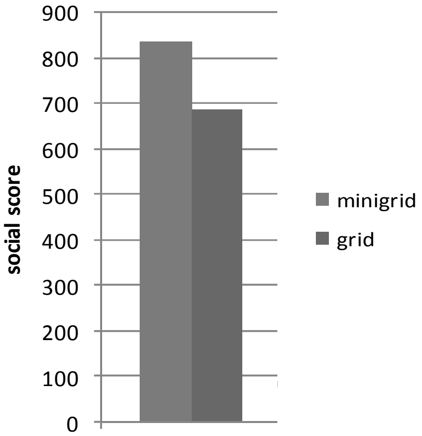
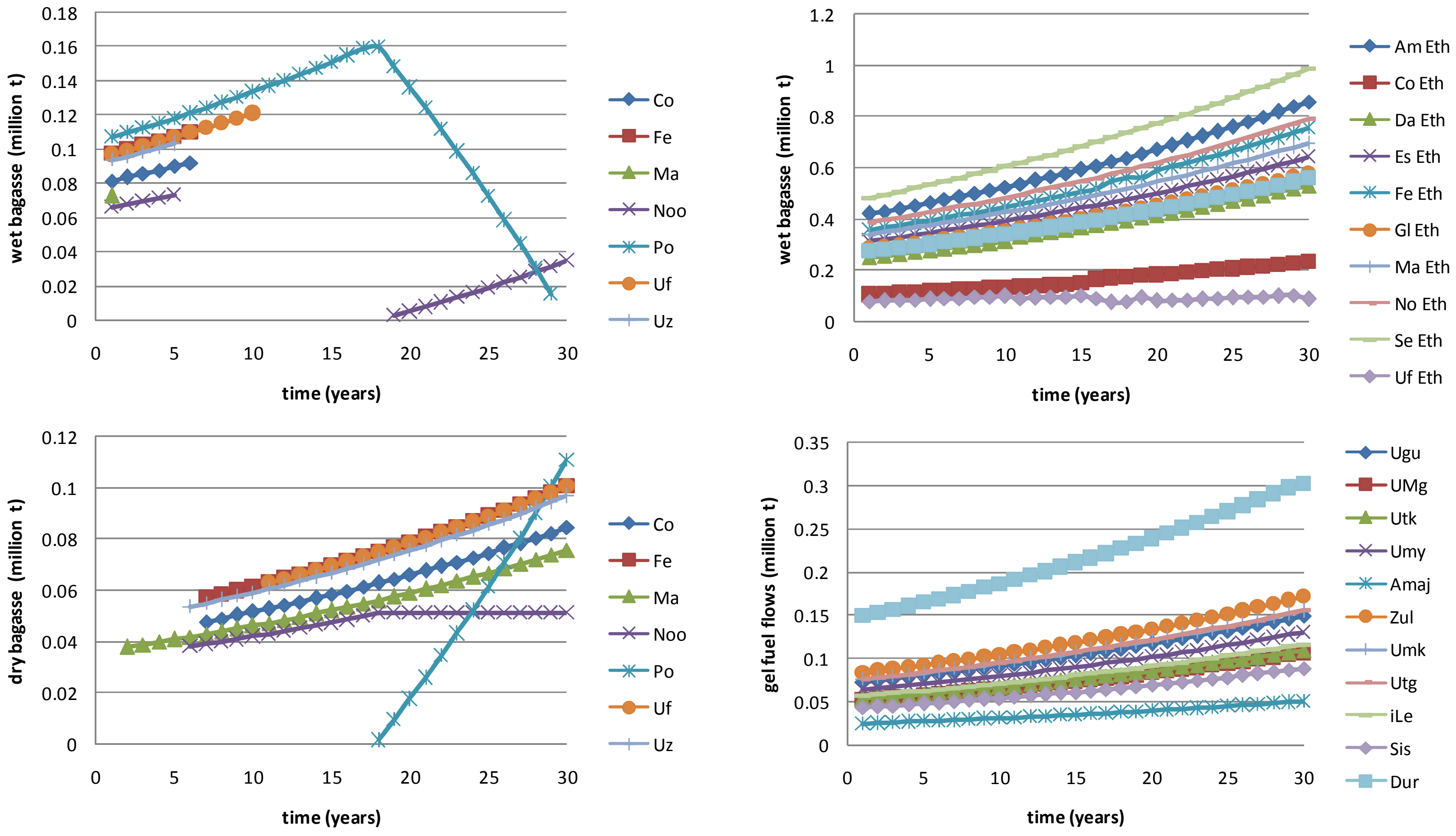


Figure 8-11 Social score is only influenced by the availability of a mini-grid

on investment decisions. However, it would also be possible to allocate the remaining bagasse with a view to minimising CO_2 emissions. This raises the issue of preference, which influences which objectives are judged to be more important than others. The choice of NPV indicated a preference of profitability over CO_2 emission abatement in this case. This is a discussion which will be revisited during multi-objective optimisation of the network, where a preferred performance will have to be chosen form a range of Pareto optimal solutions.

While 12 mills are situated in seven municipal regions in KZN, only one mill in each region, i.e. a total of seven mills, is required to generate power in order to completely meet the demand for electricity. All these mills switch to pelletising bagasse in order to maximise the power output from the available bagasse to free up bagasse for ethanol production. Most of the bagasse available is used to achieve the highest social score. Only Pongola, the mill that is furthest from Durban and closest to Majuba power station has bagasse in excess of that needed to satisfy rural energy demand. As a result, Pongola invests in a large pelletising capacity and exports more than half of its bagasse to Majuba. (The flows of bagasse to Majuba are not shown in Figure 8-12 as they do not contribute to the social score.) Initially all the dry bagasse is sent to Majuba, but after 18 years the dry bagasse is used for rural power production at Pongola instead (as can be seen in) and only the remaining dry bagasse, as well as remaining wet bagasse is sent to Majuba (km). In this case wet bagasse is feasible to transport due o the proximity between Pongola and Majuba. However, the delivery of wet bagasse to Majuba stops after 25 years due to excessive transport costs. The excess bagasse from these mills and the bagasse from those mills that generate no power is sent to ethanol production and subsequently turned to gel fuel. Only wet bagasse is used in this process. The gel fuel is then distributed to all 11 regions to satisfy the fuel demand. This network structure and operation is however highly unprofitable, generating losses of 124 billion ZAR. The problem lies in the fact that the mills and the ethanol producer invest in capacities allowing them to satisfy the highest regional power and combined ethanol demand over the 30 year time frame, which is reached in the final year based on the assumption that bagasse stock will grow at a rate of 2.5% a year. In other words, the plants would only operate at 100% capacity in the final year. This investment strategy is followed in order to be able o satisfy rural energy demand fully, which would not be possible if lower capacities were installed.

The satisfaction of the total rural energy demand still leaves some excess bagasse. A quick comparison between Figure 8-10, which shows the maximum possible flow of dry bagasse, and Figure 8-12 **Error! Reference source not found.**a) shows that only a fraction of total available bagasse at each mill is required for power generation. Flows of dry bagasse stay below 120,000 tons when more than 200,000 tons are available at all mills. From a cost perspective, the most attractive option is to send some of this excess bagasse, specifically that at Pongola, to the closely located Majuba power station. Investing in an IPP or producing additional ethanol to sell as transport fuel is not viable. is in excess of what is needed to run the IPP at maximum capacity (after 8 years).



a) **b)**

Figure 8-12 Flows of wet and dry bagasse for the network structure with the best rural energy supply: a) The wet and dry bagasse flows used by the sugar mills to generate power onsite and feed to mini-grid, b) the wet bagasse flows sent to the ethanol producer for eventual use as gel fuel, and gel fuel flows to the different regions

The results from the optimisation of NPV, CO_2 emissions and social score have shown that a network where gasification is used performs better or at least as well as combustion in all cases. It delivers more power from the same amount of bagasse while being more profitable than combustion, at least at high capacities. Also, the presence of a mini-grid substantially improves the ability to satisfy rural energy demand. In order to determine a network structure that best meets, or compromises between, all three objectives therefore has to include gasification technology and the mini-grid. The scenario including these options therefore provides the basis for the multi-objective optimisation performed in the next section.

While the choice of technology appears to be clear in this case, it has to be noted that the optimal network structures differ substantially for the different objectives. This is due to the greater flexibility or greater number of possible choices regarding network structure, i.e. which facilities and technologies are included. Determining a preferred network structure will therefore depend on the prioritisation between objectives, i.e. the preferred performance with respect to each of the three objectives that is to be achieved. Exploration of this prospect is carried out via multi-objective optimisation.

8.4.2 Multi-objective Optimisation

The multi-objective optimisation serves to show all best possible system states, as well as the trade-offs between the chosen objectives. The surface was constructed from 121 individual optimisations, which represents a compromise between computational effort and detail. The number is deemed sufficient to illustrate the trade-offs between the objectives.

Figure 8-13 shows the Pareto surface, represented as two two-dimensional views, for the previously outlined scenario. The scenario also includes CDM credits to allow otherwise unprofitable network configurations to become viable. The edges of this surface represent the individual optimisation results, i.e. the network with the overall highest NPV, highest CO_2 savings and highest social score (see Figure 8-13). To transition from one point to the next will involve the worsening performance for at least one other objective and the improvement of another. Looking at the top graph of Figure 8-13 it can clearly be seen that an improvement in the social score is accompanied by decrease in network profitability. The best social performance requires a network that is prohibitively expensive, to construct and run. Backing off from this point by about than 10%, from a score of 27 to 23, reduces cost by nearly 60 billion ZAR, or 40%. As NPV improves further, into positive performance, social performance deteriorates more rapidly. Due to the fact that social score is constrained through regional demand, and hence multiple network states can generate optimal social performance, each social score has a small range of possible NPV's associated with it.

The trade-off between NPV and the overall CO_2 emissions averted shows that these two objectives to a large extent track in the same direction. As NPV rises so do the CO_2 savings. What is interesting to note in this case is that a number of network configurations delivering a range of CO_2 savings can be adopted for a set NPV. As the social score is capped by demand constraints, it is insensitive to changes in the network that do not affect rural energy supply but may well affect CO_2 emissions averted and NPV.

The Pareto surface represents an infinite number of possible network performances and network configurations. Only a singe network structure can be implemented at time zero and this should deliver a satisfactory performance in all three objectives. A first requirement is that the NPV would have to be positive: A network configuration yielding negative NPV would not be considered even if it has otherwise good social and environmental performance, especially if financial incentives in the form of the CDM credits fail to make it profitable. At the same time, the main driver for this network is the SA government's desire to provide electrification and mitigate CO_2 emissions, so these objectives should to some extent be satisfied.

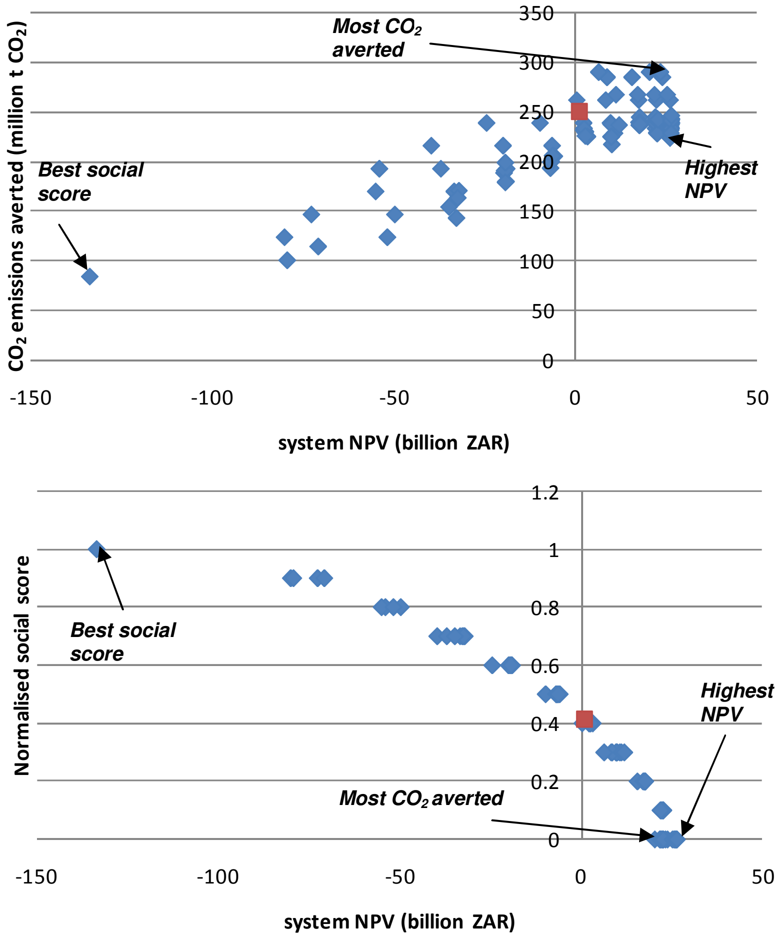


Figure 8-13 Pareto surfaces for network using gasification for both mills and IPP (CDM, mini-grid). The red point indicates the preferred network performance.

From Figure 8-13 it can be seen that for a positive NPV, CO_2 savings between 220 to nearly 300 million tons over the 30 year life time of the plants are possible. Consequently an intermediate value of 250 million tons is chosen as the cut-off value. The highest possible normalised social score for a positive NPV and CO_2 savings above 250 million tons is 1, as shown in Figure 8-11. However, a social score of 0.4, i.e. achieving 40% of the maximum possible, is deemed acceptable if this means avoiding incurring excessive costs. To determine the preferred network structure, the NPV is therefore maximised within these constraints. The preferred network development subsequently yields the following performance:

- **NPV** = 1.1 billion ZAR
- **Normalised social score** = 0.4
- **CO_2 emissions averted** = 250 million tonnes

The total power generated over the 30 year time period amounts to 307 TWh which corresponds to nearly 10,200 GWh on average yearly. However, due to the bagasse growth, the 10,000 GWh target of the SA government is only exceeded from year 18 onwards. While the network only achieves the target given by the SA government some time into the future, it nevertheless contributes significant amounts of renewable power right from the start, approximately 3,500 in year 1. Other renewable energy generation methods, such as solar or wind, could make up the difference, and be supported accordingly. The underlying network structure is discussed in the next section.

8.4.3 Preferred Network Structure

The preferred network structure is a mix of all the technologies recommended for the different objectives. The sugar mills, IPP and Majuba all receive bagasse to convert to both power and the ethanol producer to generate ethanol/gel fuel. The capacities of the various facilities are given in Table 8-4. The network flows are illustrated in Figure 8-14 for the first and 30th year. This “snap-shot” presentation is chosen to illustrate the trend of network development. It is preferred in this case as the alternative, showing flow patterns of bagasse over time as in Figure 8-6. Figure 8-10 and Figure 8-12, would make the figure appear “cluttered”, due to the dynamics and the number of active facilities, and thus make the information less accessible. Initially no bagasse is sent to Majuba and predominately wet bagasse is handled within in the network: The six mills generating onsite use wet bagasse and the majority of bagasse transported to the IPP is wet. Only Pongola and Umfolozi send dry bagasse to the IPP right from the start to overcome the high transport costs due to the great distance to Durban. However, for the onsite generation of power, these mills initially use wet bagasse. Maidstone, Sezela and KwaDukuza, the three mills closest to Durban, send bagasse to ethanol/gel production.

Table 8-4 Capacities of facilities in network delivering preferred network performance

FACILITY	CAPACITY (MW)	BAGASSE USED: DRY/WET/MIX
Union Co-op	31	Mix
Darnall	23	Mix
Felixton	30	Mix
Pongola	33	Mix
Umfolozi	32	Mix
Umzimkulu	29	Mix
IPP	971	Mix
Majuba	218	Dry
Ethanol	256,000 t/a	Wet
Gel fuel	307,000 t/a	-

The six mills that generate power onsite all supply power to six of the seven rural regions and need only a proportion of their bagasse to do so as the energy embodied in the bagasse is in excess of the rural energy demand. UMgungundlovu is not supplied with power due to its low priority factor, in other words its low proportion of unelectrified housing, though Eston and Noordsberg are both situated in the area. The gel produced from Maidstone’s, Sezela’s and KwaDukuza’s bagasse is sent to four regions: Sisonke, Umzinyathi, Uthukela and Amajuba. The first three regions have the highest need for heating and cooking. Amajuba on the other hand has the smallest energy demand of all regions and this demand can be easily fulfilled with the limited gel available and the satisfaction of this demand also raises the social score. While several other regions have a higher demand for paraffin replacement, their demand outstrips the gel fuel available.

As time progresses most of the wet bagasse is pelletised. Only KwaDukuza, Maidstone and Noordsberg, which are close to Durban where the IPP and ethanol producer are located, continue with wet bagasse deliveries. This trend is caused on the one hand by a need to avoid the rising transport costs for the bagasse deliveries to the IPP and Majuba. On the other hand, the sugar mills, for which transport is not an issue, switch to dry bagasse to benefit from the improved heating value, thereby generating more power and substituting more CO_2. The switch to pelletised bagasse by the sugar mill power generators is not driven by profit, but by the need to satisfy rural energy demand and mitigate CO_2 emissions by increasing the possible power output, which is possible if dried bagasse is used instead of wet bagasse. The investment in pelletisation facilities and the cost of running these cancels out the increase in revenue from higher power output. The larger the mills are, the sooner they switch to dry bagasse production as the bigger mills benefit from the economies of scale associated with investing in bagasse pelletisation. However, some mills continue using the wet bagasse that is in excess of the drying capacity installed and use it onsite, such as Union Co-op, Darnall, Umzimkulu, or they send it to the IPP, such as the more closely situated Noordsberg. Mills that pelletise bagasse and barely break even doing so would however be unlikely to make this decision in practice. This is a barrier to implementing the sustainable development strategy chosen for this case study, which is the use of bagasse to substitute coal-based power.

In addition to rising costs, the bagasse availability at the sugar mills increases. As a result the mills that are farthest from the IPP, specifically Amatikulu, Umfolozi and Pongola, discontinue deliveries as soon as the supply from more closely situated mills rises to the point where these can satisfy the demand. Umfolozi, Pongola and Felixton start sending their excess bagasse to Majuba. Sezela ceases bagasse deliveries to ethanol and instead starts pelletising bagasse and supplying the IPP.

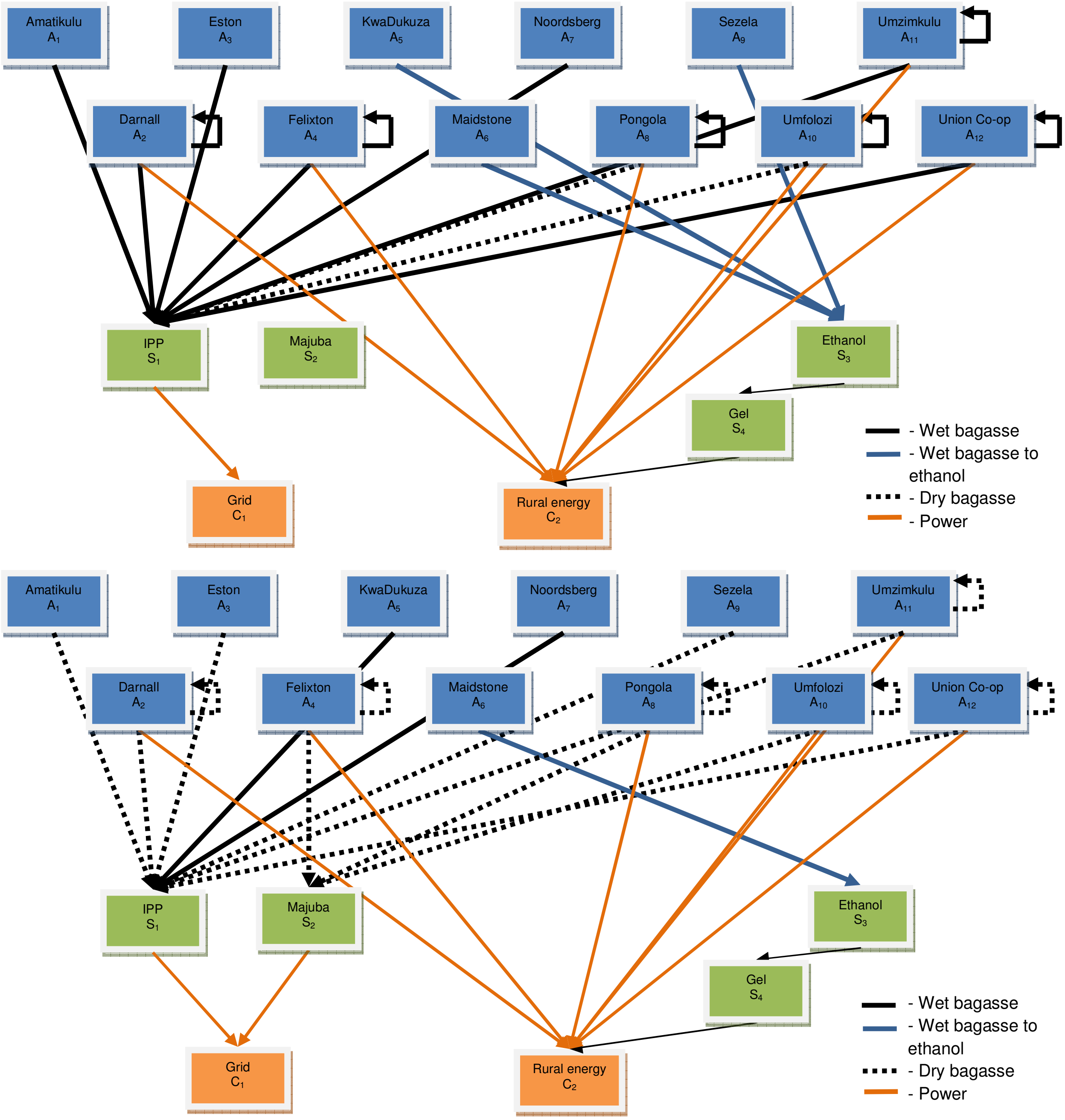


Figure 8-14 Preferred network structure in year 1 and 30

Only Maidstone continues suppling bagasse to gel production. Full satisfaction of fuel demand can only be maintained for Sisonke and Amajuba, but deliveries to Umzinyathi and Uthukela virtually stop, falling by more than 90%.

While the overall system NPV is positive, not all facilities within the network are profitable: It was noted that the sugar mills that pelletise bagasse barely break even. Furthermore, the ethanol production is "subsidised" by the profitable operation of the IPP. Even if the IPP, bio-ethanol and gel fuel producers were owned by the same company, it is consequently unlikely that the IPP's profits would be used to keep ethanol and gel fuel production running. This is an example of where the top-down approach to industrial network analysis falls short, by including an option as attractive that would not be included if the interests of the individual network agents were considered. If it were likely that they would make losses by investing in a certain technology, then agents would be disinclined to go ahead with the investment. Saying that agents are only driven by economic gain would be oversimplifying how agents make decisions, however, they are driven to no insignificant extent by an interest to maximise their *own* strategic (economic) advantage and they try to position themselves accordingly. In reality, a network does not develop based on a single overarching objective (unless an agent in the network dominates to such an extent that it could enforce its interest), but emerges based on the actions of individual agents driven by their individual objectives. This illustrates how agent behaviour may be a barrier to sustainable development, which was listed as a possibility in the discussion of barriers in Chapter 2. However, the intent of industrial network analysis is to determine what the best *possible* performance is, not the *probable* performance, and the question subsequently is how this a barrier could be overcome.

The preferred network structure identified in this section would only become feasible if ethanol and gel fuel production were to become cheaper or if capital or operating subsidies were made available in order to promote the replacement of paraffin through gel fuel. Lowering ethanol or gel fuel prices does not really lie within the control of government or network agents but is a development driven by national and international markets. Consequently, to overcome the barrier of high bio-ethanol and gel fuel production cost, the latter incentive would be more likely to be deployed and encourage investment. Alternatively, the underlying assumption that technology costs are constant through time and that all investment has to occur in year one could be re-examined. The model could be adapted to consider 1) the possibility that bio-ethanol and gel fuel production will become cheaper as the technology, especially for bio-ethanol production, fully matures and 2) to allow investments to be deferred to a later time. This reflects types of model form uncertainty (mathematical expression), however, the effect of these particular uncertainties will not be explored here.

The network development is driven by the initial assumptions about the structure and performance of the network, the temporal changes and the chosen objectives. It is likely that changes in any of these would lead to different network configurations. To determine to what extent the preferred network structure and development determined in this section holds under different conditions necessitates an uncertainty analysis, which is the subject of the next section.

8.5 CONSIDERATION OF UNCERTAINTY

8.5.1 Uncertainty in Model Form: Mathematical Expression

Literature sources cited a range of values for the capital and operating cost of biomass combustion and gasification. The cost curves used for the deterministic model in this case study were fitted to all available data, thereby capturing average costs. However, the data varied significantly between some sources. In order to determine to what extent a different cost curve influences network performance and structure, the model is run with curves fitted to data from the individual sources, which were Bridgwater et al. (2002) and Williams (2005), and compared with the average data. These fittings however, maintained the economies of scale, i.e. continued to be power functions. Focusing on the values of coefficients and exponents in this power law relation, allows model form uncertainties to be translated into model parameters uncertainties instead. Again, the functions were piecewise linearised for use in the model (see Appendix E). The effect of using different cost curves is discussed in section 8.5.4.

8.5.2 Parameter Uncertainty

The only uncertain parameter is the discount rate used. The discount rate determines the return on investment and therefore also the attractiveness of an investment. For this reason high risk investments are usually assigned higher discount rates to indicate that the higher risk has to be balanced by the higher expected return. The bagasse-energy models are therefore rerun using a discount rate of 20% to assess its effect on profitability.

8.5.3 Outcomes of Parameter Importance Testing

Uncertainty importance is assessed here by interval analysis, i.e. by variation of parameters individually, not simultaneously. The importance of an uncertain parameter is determined by the deviation from the deterministic objective value caused by the parameter variation. This has the draw back that the effects of interactions are not considered, but as the model is primarily linear in terms of its parameters, this is assumed to be acceptable. The benefit of this method, however, is that significantly fewer computational runs are required and the effect of each individual parameter variation on network performance and structure is clearly illustrated. While a substantial change in objective value can mean the difference between an investment in the network being attractive or not, it is even more important to note the sensitivity of the underlying *network structure* to such a change. "Sensitivity" in this case implies if, and to what extent, network structure is affected, for instance, if network nodes are included or dropped compared to the expected case, or whether flows or capacities are substantially altered. If the optimal network structure is very sensitive to changes in model parameters then investing in this structure may be risky, as it would perform sub-optimally for most realisations of the uncertain parameters.

The results of the importance testing are shown in Table 8-5, Table 8-6 and Table 8-7 for the NPV, CO_2 emission and social objectives respectively. Only a comparatively small number of parameters appear to have a significant impact on the objective values: For the NPV, 9 out of 45 parameters tested change the objective value by more than 10%, 5 of 26 for the CO_2 emissions and 3 of 27 in the case of the social score. None of the parameters that changed the objective value by less than 10% resulted in a significant change in model structure: the same nodes remained active, though bagasse flow rates changed by a small degree, if at all. The tables indicate the change of network structure that the change in parameter precipitated. The (H) indicates the change observed when the parameter was set to its highest value, whereas (L) indicates the effect when the parameter was set to the lowest value. The fact that fewer parameters have been identified as important compared to the FFD analysis performed for the wood products case study can be specific to the data informing this case study, but could also be explained by the fact that the interaction effects of the parameters variations, even if apparently small, increase the importance of all or some of the individual parameters.

It is interesting to note that the discount factor has the highest impact on NPV but does not influence network structure. The price of electricity only impacts network structure if it falls below that value where the network NPV becomes negative. This is 260 ZAR/MWh for the deterministic case. Otherwise all parameters merely influence the flow rates, but the IPP remains the preferred destination. The moisture content of bagasse and the operating hours anticipated for wet bagasse influence the relative amounts wet and dry bagasse used.

Table 8-6 lists the most important parameters for the environmental objective. The optimal network structure in this case is also not heavily affected by parameter variations, with the only variable changing being the amount of bagasse used by the network. The maximum power that can be generated either increasing or decreases, thereby averting less or more CO_2 that would otherwise be provided by coal, but the network structure remains the same: power is generated onsite to the greatest extent possible.

Table 8-5 Importance of the parameters influencing NPV

PARAMETER	DEVIATION (%)	EFFECT ON STRUCTURE*
discount factor	271	(H) no structural change (IPP generates, Pongola supplies Majuba) (L) no structural change (IPP generates, Pongola supplies Majuba)
price of electricity	132	(H) no structural change (L) below 260 ZAR/MWh no generation of green electricity takes place, i.e. no network is established
bagasse growth rate	102	(H) same structure, but bagasse flow to IPP increases (L) same structure, but bagasse flow to IPP decreases
bagasse yield from cane	64	(H) same structure, but bagasse flow to IPP increases (L) same structure, but bagasse flow to IPP decreases
fraction of bagasse used for onsite requirements	64	(H) same structure, but bagasse flow to IPP increases (L) same structure, but bagasse flow to IPP decreases
initial cane resource at each mill	64	(H) same structure, but bagasse flow to IPP increases (L) same structure, but bagasse flow to IPP decreases
price of CDM credits	41	(H) no structural change (L) no structural change (depending on electricity price)
moisture content of dry bagasse	20	(H) increases use of wet bagasse (L) increased use of dry bagasse
operating hours/year with wet bagasse	17	(H) increased use of wet bagasse (L) increased use of dry bagasse

*(H) effect of network structure if parameter is set to highest possible value
(L) effect of network structure if parameter is set to lowest possible value

Table 8-6 Importance of the parameters influencing CO_2 emissions

PARAMETER	DEVIATION (%)	EFFECT ON STRUCTURE*
CO_2 emissions averted per ton coal substituted	44	(H) no structural change (sugar mills generate onsite) (L) no structural change (sugar mills generate onsite)
bagasse yield from cane	12	(H) more power generated at mills (L) less power generated at mills
fraction of bagasse used for onsite requirements	12	(H) more power generated at mills (L) less power generated at mills
initial cane resource at each mill	12	(H) more power generated at mills (L) less power generated at mills
bagasse growth rate	10	(H) more power generated at mills (L) less power generated at mills

*(H) effect of network structure if parameter is set to highest possible value
(L) effect of network structure if parameter is set to lowest possible value

Transport CO_2 emissions are not included in this list. This is due to the fact that the minimisation of CO_2 emissions results in a network structure where the mills exclusively generate power onsite (as was discussed in section 8.4.1.2). The optimal solution therefore does not include transport effects and is not sensitive to changes in this parameter. However, previous modelling results had shown that over the larger distances, i.e. over 100km, the transport effects are in the same order of magnitude as the "CO_2 emissions averted per ton coal substituted", for wet and dry bagasse, though for dry bagasse obviously to a lesser extent. As a result, this parameter has to be included in the stochastic MOO as the satisfaction of a certain NPV and social score will in all likelihood necessitate transport.

The fact that certain relevant parameters are ignored because they are not part of the optimal solution is a disadvantage of using interval analysis to determine the relative importance of parameters. FFD is not expected to adequately address this issue either, especially in this case, where none of the parameter variations managed to change the optimal network structure identified. Symbolic sensitivity analysis would be a better option, as the effect of change of any parameter on the objective function can be determined.

Table 8-7 Importance of the parameters influencing social score

PARAMETER	DEVIATION (%)	EFFECT ON STRUCTURE*
household demand for electricity	39	(H) more bagasse used to generate power at mills (L) fewer mills are required to generate
growth rate of rural energy demand	35	(H) all bagasse used to generate power or produce gel fuel (i.e. demand exceeds supply) (L) fewer mills generate power or send bagasse to ethanol production
household demand for fuel	18	(H) more bagasse used (L) fewer mills send bagasse to ethanol, as less gel fuel is required

*(H) effect of network structure if parameter is set to highest possible value
(L) effect of network structure if parameter is set to lowest possible value

The social score is primarily influenced by parameters describing regional energy demand, and therefore the extent to which the rural energy demand can be satisfied. As there is an excess of bagasse and an upper limit to the rural demand, the bagasse availability has a lesser effect in this case because the social score is constrained by the lower rural demand.

The other important parameters which affect the social score are the regional priority factors. These were excluded from the uncertainty analysis for the following reasons:

- The census data is seen as reliable. Consequently the bases for the priority factors, namely the estimate of the proportion of unelectrified housing/proportion of paraffin use for heating are assumed to be accurate. Furthermore it has to be considered that the priority factors are normalised. As a result their magnitude would remain between 0 and 1.
- The regions chosen for energy supply would only switch if the relative order of importance were to change. For this there is no indication.
- The social score is a constructed indicator with no direct physical meaning. It is instead a guide to which regions should be supplied to the greatest extent possible. The exact value of the social score is therefore not of prime importance and further supports the choice to work with normalise values.
- The analysis is intended to show indicative trends. Great accuracy in a constructed factor is not a requirement to achieve this. This insight relates to the statement in Chapter 6 (section 6.3) that the degree to which uncertainty should be interrogated is influenced by the purpose of analysis.

The results of the deterministic optimisation in section 8.4 are compared in the following section to models where the uncertainty in model form, model parameters and empirical parameters is considered explicitly. First off, a stochastic model is developed to account for the effect of uncertainty in the empirical parameters[41]. For this, the possible realisations of the empirical parameters are classed into best/highest, worst/lowest and expected states. Each of these states is assigned a respective probability of 25%, 25% and 50%. To assess the effect of different cost curves, the stochastic model is rerun with different discount rates and cost curves, as discussed in 8.5.1 and 8.5.2. A sensitivity analysis will also be performed to determine if the outcomes of the stochastic model vary significantly if the best/worst and expected states of the empirical parameters are assigned other probabilities.

8.5.4 Outcomes of Uncertainty Modelling

The analysis in this section demonstrates the nested approach described in 6.5, which considers all possible combinations of uncertainty in mathematical expression, model and empirical parameters Figure 8-15 therefore shows the best possible performance of the network under the proposed strategy to use a biomass waste to substitute coal-based power and provide rural energy

Figure 8-15 shows the stochastic Pareto surfaces for the three mathematical expression uncertainties tested (capital and operational cost curves fitted to data by Williams, data by Bridgewater, and the averaged literature data that was also used as the basis for the deterministic case), as well as the different discount rates. It is clear that both the use of different cost equations as well as the use of different discount rates has a significant impact on the NPV. When using William's data for cost assessment, NPV's as high as 60 billion ZAR can be achieved, compared to 35 billion when using Bridgewater's data and 40 billion ZAR for the averaged data, though in all cases the highest NPV is delivered by identical network structures, i.e. the IPP generates. At the same time, worst economic performance could range from losses of 120 billion ZAR to nearly 150 billion ZAR, depending whether William's or Bridgewater's data was used for cost estimates.

The discount rate has an equally pronounced effect. The use of 20% instead of 8% as a discount rate means a decrease in best NPV from about 40 billion ZAR to about 10 billion ZAR in the case of the average data, and a drop from 35 billion ZAR to 10 billion ZAR for Bridgewater's cost data. When using William's cost data, the effect is even greater, lowering highest NPV from nearly 60 to 20 billion ZAR. An additional affect of the higher discount rate, however, is that the losses would be less extreme, limiting losses to 25 billion ZAR instead of a 110 billion ZAR for the averaged cost curves.

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[41] An explanation of how the stochastic model is constructed is provided in Appendix C.1.1

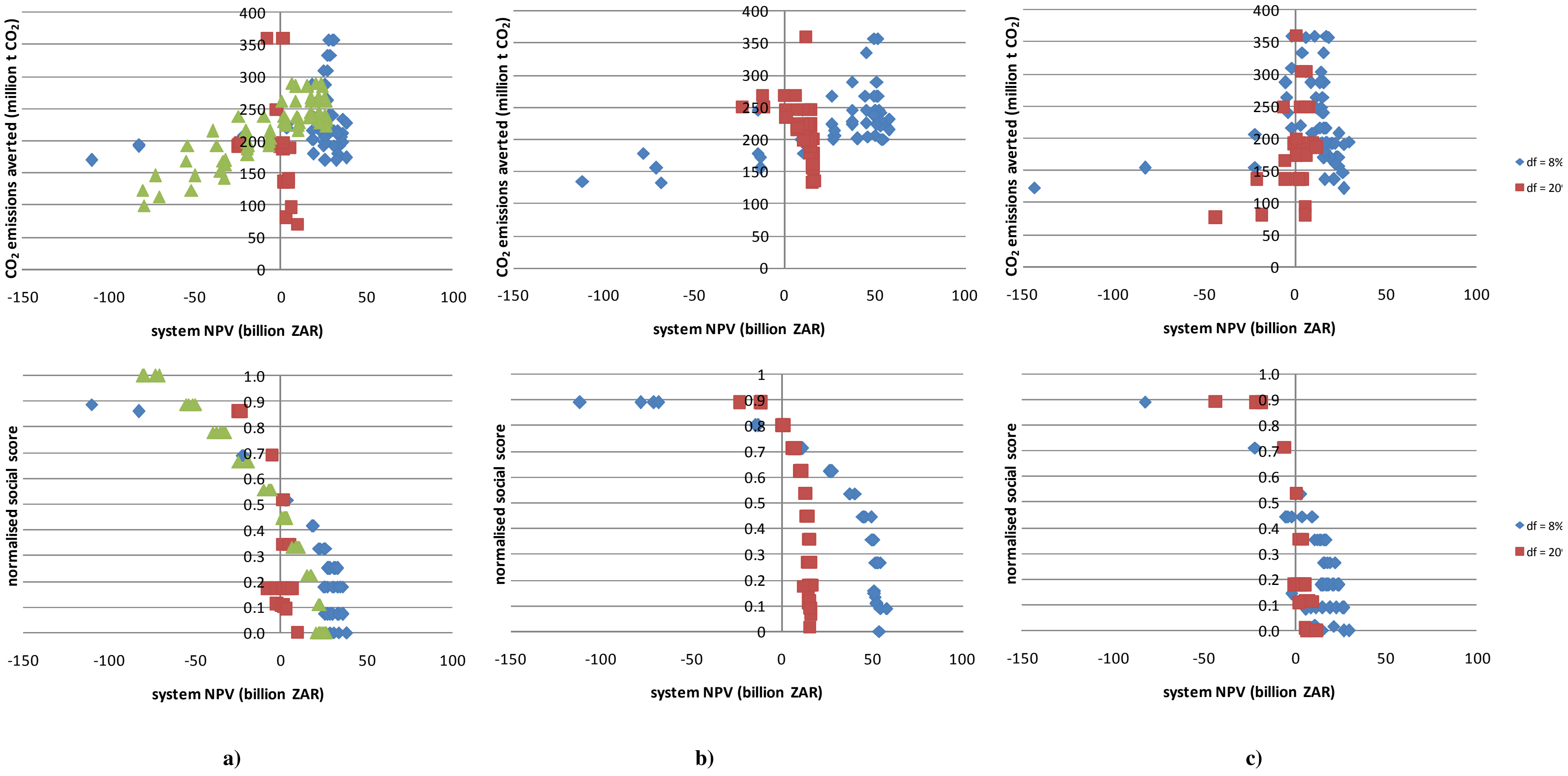

Figure 8-15 Stochastic Pareto surfaces for 3 different model forms for combustion/gasification capital and operational cost: a) average fit, b) Williams, c) Bridgewater (Note: Legend applies to a), b), and c)).

Within the constraints on performance used for the deterministic optimisation (normalised social score $\geq$ 0.4, CO_2 emissions averted $\geq$ 250 million t), however, network structures and development pathways can be identified that achieve a positive NPV. These network structures are assumed to be similar to the networks identified during the deterministic analysis as providing maximum CO_2 mitigation and maximum NPV in the deterministic case, less the network structure identified for maximum rural electrification. Whether this includes the preferred network structure identified in section 8.4.3 will be addressed in the next section.

The uncertainty in cost curves and discount rates only affects the NPV objective. Only the empirical parameter uncertainty plays a role with regards to the CO_2 emission and rural energy provision objectives. Figure 8-15a) includes the deterministic Pareto surface (green) for comparison with the stochastic Pareto surface, which is based on the same equations and a discount rate of 8% (blue). The deterministic Pareto surface and the stochastic one, which hedges against empirical parameter uncertainty, overlap to a large extent, however, there are some noteworthy differences. The range of economic performance is larger for the stochastic case, which makes sense since the consideration of the best and worst cases increase the scope of possible performance. Environmental performance overall is lower for the deterministic case, ranging from 100-300 million tons CO_2 averted, compared to 160-360 million tons for the stochastic case. The best achievable social score under empirical parameter uncertainty is lower, achieving only 90% of the maximum possible social score identified in the deterministic analysis in section 8.4.1.3.

In this case, the best NPV achievable is more affected by the discount rate used, a model parameter, than by the different cost curves, a model form. This can be attributed to the particularities of the case study, and should not be interpreted as a general trend. The discount rate affects all cost calculations, whereas the different model forms only affect the costs of sugar mills and the IPP, should these invest/be built. Furthermore, the cost curves do not deliver very different estimates on costs, whereas the difference between a discount rate of 8% and 20% is substantial. The effect of empirical parameter uncertainty also has a significant effect, as seen by the different shapes and ranges of the deterministic (green) and stochastic (blue) surfaces in Figure 8-15a), this does not provide sufficient information to judge if its effect is more or less pronounced than that of using different cost curves. This discussion has nevertheless highlighted that the different forms of uncertainty - model form, model parameter and empirical parameter - all have significant impacts on the possible performance and that the explicit interrogation of the effect of uncertainty through the use of the uncertainty analysis framework described is Chapter 6 is able to elicit this effect

While this section has provided insight into the effect of uncertainty, the question that remains to be answered is whether the network structure identified in section 8.4.3 is robust.

8.5.4.1 *Feasibility of preferred network performance and structure*

To determine preferred network performance under uncertainty, the same constraints on network performance that were applied to the deterministic case are used. This enables a direct comparison between the deterministic and stochastic models and makes it possible to determine the influence of empirical parameter uncertainty. The constraints are a minimum normalised social score of 0.4 and a minimum of 250 megatons of CO_2 avoided. Under these conditions the following performance is achieved under uncertainty:

- **NPV** = 14 billion (up from 1.1 billion ZAR)
- **Normalised social score** = unchanged (0.4)
- **CO_2 emissions averted** = unchanged (250 million tonnes)

A similar effect is noted as in the first case study: the performance under uncertainty can be better than in the deterministic case. This is also attributed to the fact that network performance under the best possible empirical parameter realisations improves more than it deteriorates under the worst conditions. Figure 8-16 shows the Pareto surfaces of the best and worst case scenarios, as well as the deterministic and the stochastic surfaces for comparison.

Over the 30 years, 310 TWh of power can be generated, which is slightly more than the 307 TWh of the deterministic case. The fact that the normalised social score is lower than for the deterministic case while virtually the same amount of power is being generated indicates that under uncertainty costs are higher. It is therefore more difficult to reach profit target and the satisfaction of rural energy demand has to be sacrificed as a result, if only to a small extent. This interpretation is supported by the underlying network structure. The capacities of the active network facilities are shown in Table 8-8. The capacities of the deterministic case are also included for comparison.

Table 8-8 Capacities of facilities in network delivering preferred network performance

FACILITY	CAPACITY (MW)	BAGASSE USED: DRY/WET/MIX	CAPACITY DETERMINISTIC MODEL (MW)
Felixton	23	Mix	30
Union Co-op	5	Mix	31
Darnall	26	Mix	23
Noordsberg	11	Mix	-
Pongola	1	Dry	33
Umzimkulu	24	Mix	29
Umfolozi	4	Mix	32
IPP	1065	Mix	971
Majuba	400	Wet	218
Ethanol	203,000 t/a	Wet	256,000 t/a
Gel fuel	244,000 t/a	-	307,000 t/a

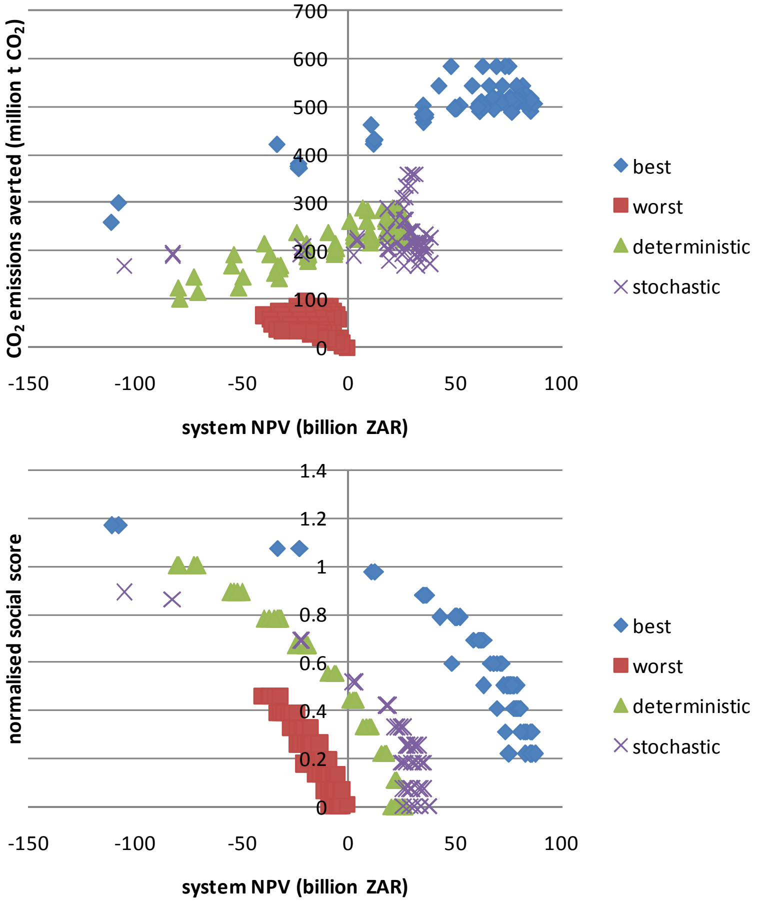

Figure 8-16 Pareto surfaces for the network performance under best, worst, expected (deterministic) conditions and comparison with the stochastic Pareto surface.

Despite the fact that this case study deals with the design of a new network, and that as a consequence the optimisation has greater flexibility with respect to the network structure and performance it can choose, the network identified for the stochastic optimisation is similar to that identified in the deterministic optimisation. However, there are some notable differences: The installed capacity recommended by the stochastic model for the sugar mills is lower in all cases. In the case of Pongola, Umfolozi and Union Co-op the capacity has dropped to only a few MW. However, one more region is now supplied with power: Noordsberg is generating in UMgungundlovu, a region which previously did not receive distributed power via a mini-grid. The capacities for the gel fuel production also dropped, from nearly 307,000 tons per year to about 244,000 tons per year. Gel fuel production is again only feasible due to the profitability of the other generators.

The IPP and Majuba, on the other hand are generating at significantly higher capacities. Capacity rose by nearly 10% for the IPP, whereas the amount co-fired at Majuba increased by over 80%. At 400 MW, the amount bagasse co-fired by Majuba is the maximum that is allowed to be co-fired to prevent adverse effects on down-stream equipment.

The flows in the network for year 1 and 30 are shown Figure 8-17. Initially no bagasse is sent to Majuba. Seven mills invested in pelletisation and consequently send predominately pelletised bagasse to the IPP. Mills that send wet bagasse in any notable amounts are the closely situated Darnall, KwaDukuza and Maidstone. The mills meanwhile generate with mixtures of wet and dry bagasse, using as much dry bagasse as is in excess of what is needed for export. The mills that generate at very small capacities, namely Union, Umfolozi and Pongola require only a small amount of bagasse to run, and therefore can continue using mostly dry bagasse to maximize their power output. Noordsberg, Felixton and Umzimkulu initially also make use of the dry bagasse onsite. Darnall and Umzimkulu on the other hand generate with predominately wet bagasse.

Six mills send bagasse to ethanol production. Maidstone again is the biggest supplier as it is closest to the Durban and therefore least affected by transport costs. The other mills are Darnall, KwaDukuza, Eston, Noordsberg and Sezela, however, all of these only send less than 100,000 tons, less than half as much as Maidstone's 191,000 tons. The gel fuel produced from this bagasse is used to satisfy demand in all regions except for Durban. Sisonke, the region with the highest priority factor, is supplied with sufficient gel fuel to over its demand. Most other regions such as receive gel fuel that enables them to cover a substantial part of their rural fuel demand but whether the demand is fully satisfied depends on the demand realised. Zululand and Umkhanyakude receive very little, less that 25% of their expected demand.

As time progresses and the transport costs and bagasse availability both rise, some of the mills that are further away, such as Umfolozi and Pongola, cease their bagasse deliveries to the IPP and let other mills take over with bagasse deliveries. At this stage Noordsberg, Felixton and Umzimkulu switch from dry to wet bagasse for onsite use, sending the dry bagasse to the IPP. Felixton, Pongola and Umfolozi send their dry bagasse to Majuba.

Starting from year 9 and 12, Amatikulu and Noordsberg divert excess wet bagasse to ethanol/gel fuel production, thereby allowing Durban to also receive gel fuel.

The network structure discussed here is likely to perform better than the deterministic preferred network structure as different possible realisations of the future have been hedged against. However, the preferred network structure has become much more complex. While this may be the best management of the network in theory, it can be debated whether the switching of bagasse delivery from one destination to another, and the simultaneous delivery of bagasse to several destinations, are practical. It is likely that the IPP and Majuba would prefer to enter long-term contracts for bagasse receivable from a few specific mills to ensure security of supply. The same may be true for the mills that may prefer one consistent destination for its bagasse rather than repeatedly adapting the destination based on the current situation in the network. The results delivered here could provide a basis for further evaluation where the bagasse from each sugar mill is designated to only one particular destination. This can be explored with the optimisation routines, in which case the bagasse flow between the two facilities, and/or capacities to be installed, would the variables to be optimised.

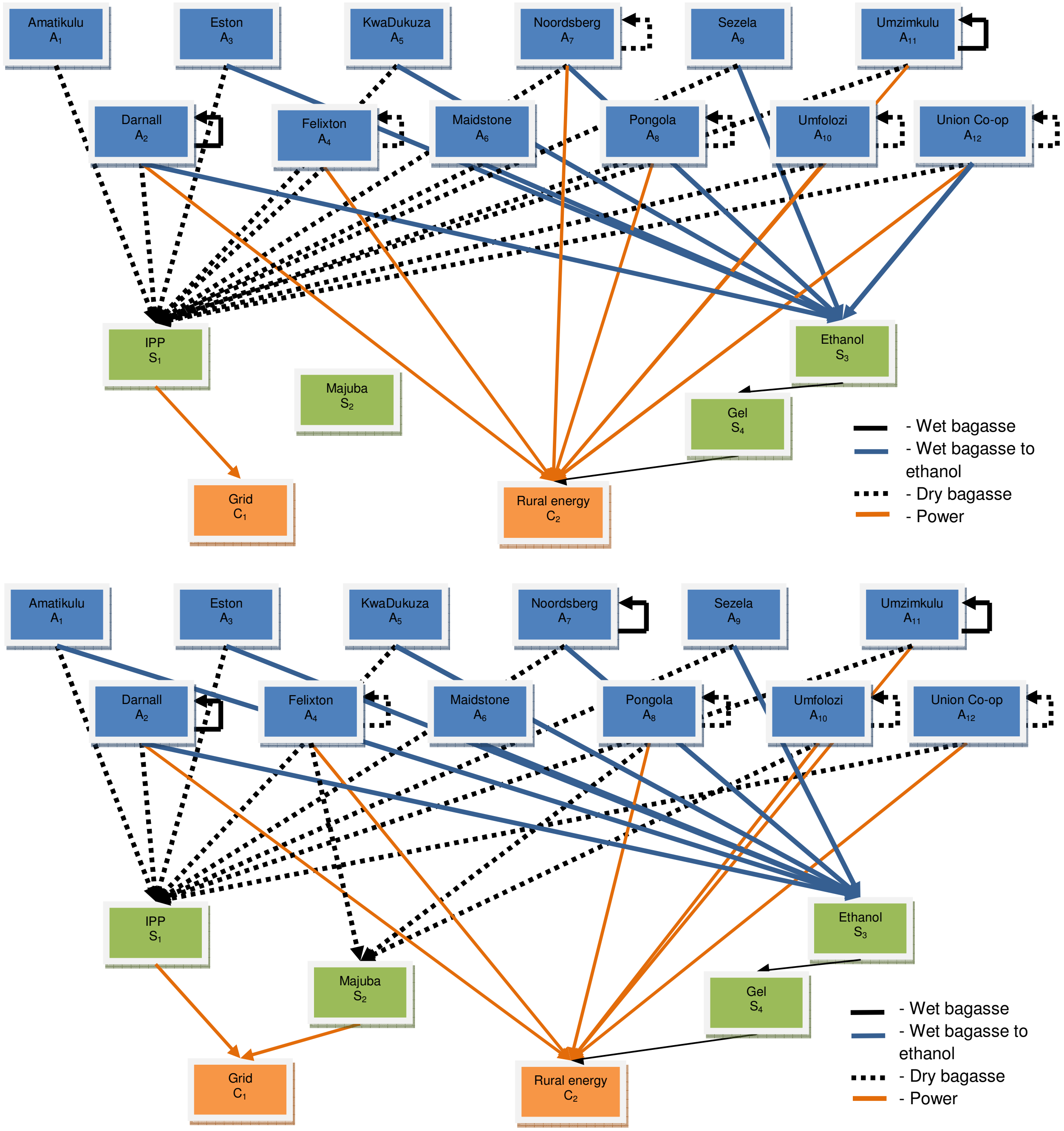

Figure 8-17 Preferred network structure under consideration of uncertainty in year 1 and 30

Alternatively, this possibility could be explored via simulation. Simulation could explore the performance of a network structure and flows defined by the modeller, preferably using input from the network agents concerned. For instance, if Eskom is interested in receiving a constant amount from Pongola and Umfolozi for co-firing at Majuba and wants to evaluate the benefit of such a move, these expectations can easily be coded into a simulation model and the performance assessed. This would be an advantage over optimisation, where it is impossible to *pre*define a particular network and network development pathway. In fact, predefining the decision variables would defeat the purpose of an optimisation. Decision variables are the variables that the optimisation has to be free to manipulate in order to determine best performance with respect to an objective function.

The stochastic optimisation performed in this section considers the possibility of different realisations of the world occurring. Consequently it is expected that the network described here is strategically better positioned to address the sustainable development issues of coal use and CO_2 release than the optimal network structure identified during the deterministic analysis in section 8.4.3. However, as the probabilities assigned to the three states of the world are estimates, the question remains if preferred network performance, as well as structure and development, would differ significantly if the probabilities of the best and worst states of the world being realised would change.

8.5.4.2 Evaluation of model sensitivity to different possible realisations of the world

In this section the robustness of the stochastic solution is evaluated. For this, two additional stochastic MOO's are undertaken, one where the "best", "worst" and "expected" realisations of the world each have equal probability of occurring (all 33%) and one that is close to the deterministic case, with the expected case most likely (80%) and the best and worst cases having an equal probability if 10%. The results are compared to the deterministic and the already generated stochastic Pareto surface where the respective probabilities were 25%, 25% and 50%. The results of these stochastic optimisation runs are shown in Figure 8-18. The values in brackets in the legend of the figure indicate the probabilities of the "best", "worst" and "expected" realisations of the world occurring.

The stochastic surfaces all have much greater spread than the deterministic analysis, with possible NPV's ranging from nearly 50 billion ZAR to -185 billion ZAR and CO_2 emission averted ranging from 100 to more than 350 million tons. Social score represent the only exception, as under uncertainty only 95% of the maximum expected social score appears to be attainable. The case where the probabilities for the best, worst and expected cases are equal has the largest spread, whereas the case that most closely approaches the deterministic case (10/10/80) has the smallest, and consequently most closely resembles the deterministic Pareto surface. To determine whether the network performance indicated by the deterministic and stochastic analysis is attainable under this expanded consideration of uncertainty, the constraints that were used for the deterministic and stochastic optimisation (CO_2 emissions averted $\geqq$ 250 million t, normalised social score $\geqq$ 0.4).

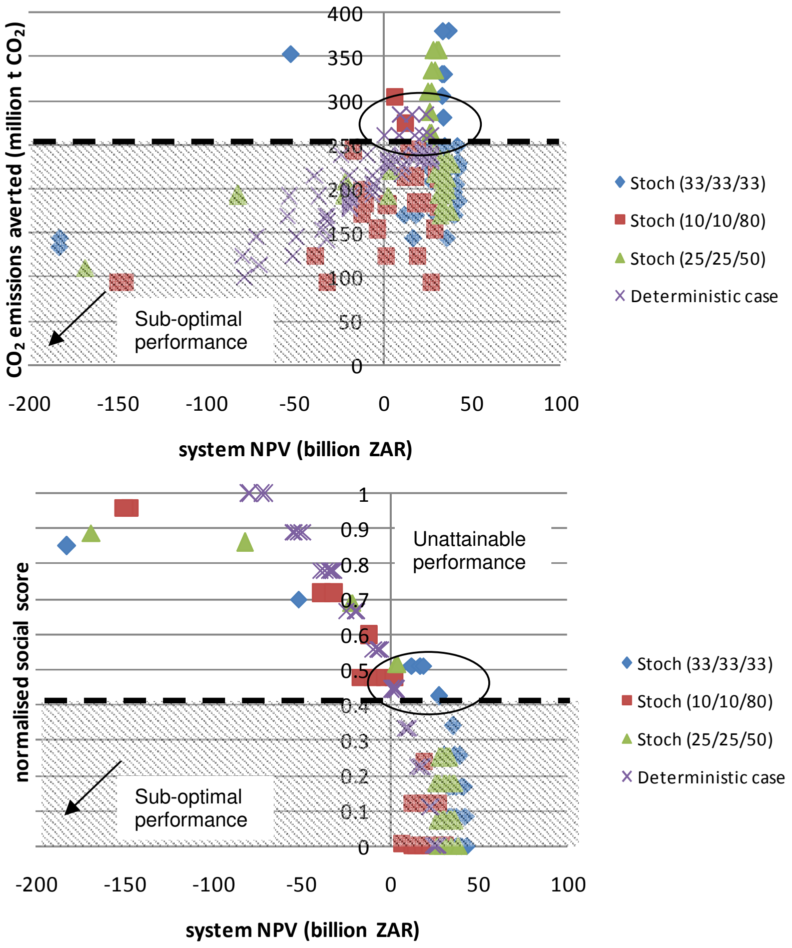

Figure 8-18 Pareto surfaces of the deterministic, and the various stochastic Pareto surfaces

Figure 8-18 also shows the constraints as dashed lines, and the shaded areas indicate the performance that consequently becomes unacceptable. If one again maximises for the NPV, the performance within the encircled areas becomes the preferred solution. The performance of the case where all realisations of the world have equal probability of occurring (33/33/33) delivers very similar performance to the initial stochastic case modelled (25/25/50), indicating that the underlying network structures that give rise to this performance are similar. However, in the case that the best and worst cases each have a 10% chance of occurring and the expected case a 80% chance of occurring, it can be seen that the required environmental and social performance cannot be attained at all. If one now considers that a negative NPV would be unacceptable for practical implementation of the network, and that the Pareto surfaces only represent the *best* possible performance (the sub-optimal, but possible performance range of the network lies under the surface, in the direction of the arrows in Figure 8-18), then there is a real chance that the desired network performance may not be attainable and that the investment in the preferred network structure described in 0 above constitutes a risky investment.

In this case this network may not be able to deliver the high standard of performance desired. Consequently there are three options:

- **Moving along the Pareto surface:** A network structure can be adopted that sacrifices social score for the sake of improved environmental and economic performance. This would likely mean abandoning ethanol production, which was shown as being expensive, and instead investing more in the IPP and decentralised generation at the mills.
- **Reducing uncertainty:** Additional research could be done to try and obtain more accurate technological and cost data that would reduce the spread of Pareto optimal performance and thereby increase the confidence in the network performance and structure identified in 0.
- **Backing off from the Pareto surfaces:** It could be determined if the constraints on the environmental and social score can be relaxed. Compared to the current situation, where no large scale biomass-based power is generated and where rural energy supply remains an issue, it can be argued that lower amounts of CO_2 averted and a lower contribution to rural energy supply would still represent an improvement over the current case. In this case if the chosen network does not manage to achieve Pareto optimal performance, but only sub-optimal performance, it will still be considered acceptable.

Evaluating the effect of different probability distributions gives insight into the best possible performance of the network under uncertainty in empirical parameters, and how achievable network performance within the desired constraints is. However, the assumption was made that a positive NPV and performance within the constraints imposed on the other objectives will be delivered by network structures similar to the ones identified in the deterministic and the stochastic analysis. This is not an unrealistic expectation in this case as the similar shapes of the stochastic Pareto surfaces indicate similar underlying network behaviour and changes in performance are attributed more to the changes in equations and parameters. However, this cannot always be assumed to be the case. Furthermore, the uncertainty analysis does not allow a definitive identification of *one particular* network structure that would be able to deliver "acceptable" performance with respect to all objectives with any reliability and would therefore be attractive for actual implementation.

Network operation can, at least to some extent, adjust to circumstances over time. Making wrong decisions with regards to *network structure* on the other hand, specifically the location, capacity and technology of facilities, could incur significant costs if, for instance, facilities end up as stranded assets or capacities are too large. Due to the limited ability of the stochastic optimisation to deliver clear answers concerning network robustness if the mathematical expression, model parameters and the probabilities of the best, worst and expected realisations of the world are uncertain, an alternatively approach is suggested: Instead of relying on stochastic optimisation, this approach to interrogating the robustness of a network *structure* could be based on simulation and Monte Carlo sampling. Sampling methods use algorithms that randomly vary the values of empirical parameters between runs based on the parameters' respective probability distributions, i.e. the values that are more likely are picked more often over the entire set of runs. The result of this sampling is a space showing the range of all probable performance. This space could be analysed with regards to the likelihood that performance with respect to each objective falls within acceptable bounds. If probability is high that the network delivers acceptable performance, the network structure can be implemented. However, a discussion of what constitutes "acceptable" performance and a high enough probability of acceptable performance to warrant implementation is beyond the scope of this thesis. This approach could be another avenue of future research. This has the advantage that the viability of a particular network configuration is thoroughly examined, but no clear statement could be made if this is the network configuration that is best positioned with regards to the possible realisations of the world.

8.6 CONCLUSIONS

The results of this case study indicate that electricity prices, at least for renewable energy, would have to rise above about 260 ZAR/MWh for the use of bagasse to be profitable, but also that such a network would substitute significant amounts of CO_2, promote rural development through power supply, improve health in rural communities through the substitution of paraffin, and be able to contribute significantly towards meeting the SA target of generating 10,000 GWh a year from renewable energy sources. In addition to these benefits, the bio-energy network contributes meaningfully towards the overarching environmental targets of minimising waste and substituting fossil fuels.

More generally, the aim of this case study was to demonstrate the application of industrial network analysis for the strategic *design of new industrial networks*. In the previous case study in Chapter 7, facilities already existed and markets were already established. Promoting sustainable development was therefore a matter of identifying preferred material allocation within this fixed structure with only one opportunity for new technology investment. By comparison, this case study required decisions on the location, capacity and in some cases the technology choice of several new facilities to create a new network, in addition to determining material allocation within this new network.

In an existing network the structures that may be adopted are constrained, and the optimisation targets mainly the material allocation. In the design of new networks, the (Pareto) optimal network structures and development pathways may differ substantially from each other depending on the prioritisation between the objectives. In other words, the network structures and development pathways delivering, respectively, the best social, environmental or economic performance can differ substantially from each other. Consequently the trade-offs between the objectives and the final choice of preferred performance has to be carefully considered, as this will decide which network structure should be adopted. Once a structure is adopted the ability to influence performance will be limited by the degree to which the network operation and development can be adapted.

The results of the case study also demonstrate the influence of *network characteristics*, and hence the importance of considering these explicitly in industrial network analysis. Firstly, the case study demonstrates the influence of the network environment. The objectives reflect the SA government's desire to foster rural development and to generate more power and fuel from renewable sources, thereby lowering CO_2 emissions and SA's contribution to global warming. Secondly, the case study also illustrates the importance of considering time-dependent behaviour: If the network structure and material allocation had been optimised for conditions, for instance, in the first year or the final year, two different networks would likely have been the result. By considering the dynamic changes, a network structure is chosen that best meets the objectives over the entire model time frame. As the results of the NPV maximisation in section 8.4.1.1 indicated, even the consideration of fairly straight-forward time-dependent changes in the parameters can lead to complex dynamic behaviour of the network.

This case study did not include an explicit discussion of stakeholder perspectives. As in the last case study, the government perspective was adopted, which is in line with a top-down view of trying to guide system development to achieve overarching objectives. However, for a more comprehensive analysis stakeholders will have to be involved. Some stakeholders may take a different view to that of the SA government on, for instance, the issues to address and the best strategies to pursue and their input would thereby influence what is included in the analysis. Therefore, if any form of practical implementation is to follow, stakeholder participation would be vital to industrial network analysis.

The uncertainty analysis approach detailed in Chapter 6 is able to illustrate the effect of uncertainty on optimal performance and gives an indication of the likelihood that performance within the desired constraints is achieved. Stochastic optimisation in particular can be used to identify a network that delivers best performance under empirical parameter uncertainty. However, the uncertainty analysis approach has the disadvantage that it delivers limited insight as to whether *a specific network structure* delivers acceptable performance under *all forms of uncertainty*. Under significant uncertainty, i.e. where equations and parameters are uncertain, it may be preferable to determine whether the network resulting form the deterministic analysis is able to deliver *acceptable* performance with respect to the objectives for all possible uncertainties, rather than attempting to identify a network that is *best* positioned with respect to all these uncertainties. For future research it is therefore recommended to explore the use of simulation coupled with sampling techniques to determine the range of possible performance for that particular network structure, thereby gaining insight into this particular network structure's chance of delivering good performance.

This case study also highlighted possible limitations of the top-down approach. The preferred network showed some behaviour which is unlikely to be accepted by individual agents, such as losses by the ethanol producer, and sugar mills producing pelletised bagasse even if they barely break even doing so. Industrial network analysis can indicate these barriers and highlight where action is required, thereby providing a basis for policy development. However, industrial network analysis nevertheless has limited ability to capture agent behaviour and whether proposed policy instruments would be successful. An analysis approach which focuses on capturing agent behaviour would therefore be an attractive avenue of future research. Such an approach could be used in a complimentary fashion with industrial network analysis to determine whether the preferred network identified are likely, or if an how agents could be encouraged to cooperate in a manner that the network approaches the preferred network structure and performance.

The application of the industrial network analysis to the two case studies has demonstrated the usefulness of the approach outlined in this thesis by showing that

- through the implementation of suitable sustainable developments strategies, network structures and development pathways can be identified that manage to 1) improve performance with respect to sustainable development in existing networks, and 2) promote sustainable development through the design of new networks.
- The possible presence of barriers and the importance of overcoming these to achieve maximum benefit.
- The influence of network characteristics as listed in Chapter 3 on analysis outcomes, and hence the validity of including these during the analysis of industrial networks.
- The influence of uncertainty on network performance.

The following and final chapter of this thesis provides conclusions regarding the foundations of the industrial network analysis approach, the approach itself and its application to case studies. It points out the limitations of industrial network analysis and recommendations for future research.

9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The aim of this thesis was to develop an analysis approach to investigate the contribution of industrial networks to sustainable development, and to explore strategies for intervention in order to improve system performance. This approach borrows from more mature system research fields like Supply Chain Management (SCM) and Process Systems Engineering (PSE) to extend the capacity of Industrial Ecology (IE) to capture the complexity of the network context, as well as that of network function and performance. The approach takes a top-down, prescriptive approach: “Top-down” means that sustainable development objectives are defined for the network as a whole rather than its individual units. “Prescriptive” means that the analysis focuses on identifying structures and development pathways that a network *should* adopt as they deliver best possible performance, rather than merely describing how it *could* develop. The influence of agent-behaviour was therefore not explicitly considered. Through the development and demonstration of the *industrial network analysis* methodology this aim has been achieved.

There are a number of conclusions which can be drawn from the intellectual development of the industrial network analysis approach developed in this thesis. These conclusions will be discussed in the context of

- the foundations of the approach
- the methodology itself and the demonstration of the methodology through the use of case studies.

Furthermore, the limitations of the approach will be discussed and on the basis of this recommendations are given for future research.

9.1.1 The Foundations of the Approach

Industry contributes significantly to environmental degradation as a result of resource extraction, processing of materials, distribution and use of products, and post-use disposal. Industrial ecology (IE) is a comparatively young research field that recommends a systems approach to addressing environmental issues in industry. The underlying tenet of industrial ecology, which also gave IE its name, is that industrial systems should mimic natural systems: material and energy cycles should be closed, processes should become more efficient, resources should only be used at a rate that they can be replenished, wastes released at a rate they can be assimilated. IE views industry as being made up of systems that interact with other technological and economic systems, but also interface with nature and society. Within these industrial systems, industrial facilities and organisations interact in order to deliver the products and services desired by society. As no unit in the system acts in isolation, IE argues that environmental interventions should be targeted at these systems as a whole, rather than at the individual units. This systems approach is the strength of IE and consequently IE provides the basis for the work in this thesis.

IE draws on a range of environmental assessment tools for the purpose of promoting environmentally sustainable development. However, it was argued in this thesis that these assessment tools have limitations with regards to capturing the complexity of these systems and the sustainable development context: Specifically, within the individual assessment tools in IE there is insufficient consideration of:

- the system environment
- the system's and the system environment's dynamics
- the effect of uncertainties on the robustness of solutions recommended to address sustainable development issues
- the consideration that sustainable development requires the meeting of multiple objectives, environmental, however also economic and social objectives.

A need was therefore identified to provide comprehensive analytical capabilities through which the role of strategic interventions within industrial systems can be explored. This thesis addressed this need through the development of the so-called industrial network analysis approach. To develop the industrial network analysis approach, it was decided to extend on the capabilities within the set of environmental assessment tools by drawing on other systems research, particularly PSE and SCM. The reason behind this is the greater maturity of these research fields and their experience with industrial system planning and design to achieve chosen objectives.

However, before it could be discussed how to adapt and synthesis aspects of environmental assessment tools and of analysis approaches in PSE and SCM, it was first necessary to define the *context of the proposed analysis approach*. The resulting discussion served to highlight the challenges involved in addressing environmental issues in industrial systems and the complexity of the sustainable development context. Chapter 2 dealt with the identification of environmental issues facing industry that the proposed analysis should be able to address. The chapter further discussed strategies – substitution, dematerialisation, reintegration, waste mining and waste management (Ayres and Ayres, 1996) – that are seen as able to address these issues. The recommended strategies act as guidelines for industrial network analysis to help determine what particular opportunities exist for improving performance with respect to sustainable development in a particular industrial system. The industrial network analysis then endeavours to determine their effectiveness and tailors network structure and development pathways to achieve best system performance with respect to sustainable development.

Several barriers were identified that can impede the success of strategies, including amongst others economic costs, physical limitations, technology lock-in and lacking agent cooperation. The proposed industrial network analysis can highlight some of these barriers. Furthermore, industrial network analysis was seen as a possible means to address some of these barriers through the provision of information about the benefit of implementing sustainable development strategies. For instance, this information could encourage cooperation for possible implementation. The use of regulatory, economic or social policy instruments to overcome barriers to sustainable development was also discussed, however, industrial network analysis as a technical system focused approach has limited ability to explicitly consider the effectiveness of social instruments in overcoming barriers.

Clearly, the implementation of any sustainable development strategy will have implications for the operation and structure, as well as the on-going development of the industrial system, either because cooperation from several or all concerned parties in the system is required, or due to a ripple effect if one entity in the system were to adopt a strategy.

Before it was possible to launch into the development of the industrial analysis approach, it was also necessary to specify the physical scope and level of detail of the industrial systems that industrial network analysis should be targeted at, in other words the intended *object of the analysis* needed to be defined. “Industrial networks” are a construct developed for the purpose of this thesis. They are loosely defined as a group of linked, or linkable, units which exercise or contribute to industrial activity through exchange of materials, energy, information and capital and should capture industrial activities form cradle to grave, as strategic interventions will likely have repercussions all along a product life-cycle. Industrial networks capture the inter-firm level as this makes it possible to capture technological detail of industrial behaviour while avoiding excessive simplifications and loss of detail often required to make the system model at the national or global level tractable.

In Chapter 3 a characterisation was developed for industrial networks. These characteristics influence the structure and behaviour of networks. As such, the state of some characteristics may give rise to the issues that are to be addressed, e.g. a network *source* may be non-renewable, and the adaptation of the characteristics forms part of strategies to overcome these, e.g. institute *reintegration structures* to reduce dependence on the *source* as far as possible. Others characteristics will not be set before analysis, but may be revealed during or created by the analysis, such as *dynamics*. Furthermore, the state or behaviour of some characteristics may impose barriers to sustainable development, for instance *material properties* may limit the degree of reintegration possible. In other words, the characteristics influence to what extent sustainable development can be promoted. The characterisation therefore provides a foundation for industrial networks analysis by indicating how the state and behaviour of characteristics affect network performance. In both case studies it was demonstrated that different network characteristics, such as material properties, network environment and dynamics, have a significant impact on strategy formulation and the preferred network structure and development pathway identified. Capturing the characteristics poses an intellectual challenge for industrial network analysis: The presence of dynamics of network with their changing structure and performance, the role of their external environment, as well as the significance of uncertainty underlying how the characteristics are captured makes the tackling of environmental issues in industrial networks a class of complex problems.

In a review of environmental assessment tools it was found that while many tools have the capability of considering the influence of system environment, dynamics, uncertainty and multiple objectives, none include explicit consideration of all these aspects. However, the critique also highlighted that MCDA, LCA and MFA possess attractive features. MCDA, especially, encompasses a suite of tools designed to deal with complex problems: It consists of a structuring and an analysis section, which is flexible with regards to the quantitative tool used. The problem structuring is suited to unravel the complex problem context and thereby clarify the issues that need to be addressed. It consequently addresses the challenge of engaging with the intangible influences of the *network environment* on the industrial network. Furthermore, MCDA is by definition designed to engage with multiple objectives. As a result, the structuring approach was taken over into industrial network analysis to allow:

1) consideration of the network context and any intangible aspects that would influence the strategies adopted or the assumptions underlying the quantitative models and
2) the elicitation of multiple criteria that guide the choice of preferred network structure and performance within the chosen strategy.

With regards to the quantitative analysis, LCA considers various environmental impacts of flows and not just the magnitude of flows, whereas MFA is flexible with regards to the system form it captures and easily handles time-varying behaviour. For these reasons it was recommended that the quantitative analysis of industrial network analysis be embedded in a MCDA approach, impacts of material flows should be considered (in light of the sustainable development objective, social and economic in addition to environmental impacts should be considered), and that material allocation should be able to change over the time frame of an analysis.

It was found that PSE and SCM invest a lot of research into system design and planning to ensure a proposed system or system changes are viable over the long term and achieve their objectives as best possible. This matches the aim of industrial network analysis, which is intended to be used to determine network structures and development pathways that achieve best performance with respect to sustainable development objectives for a given environmental strategy. For design and planning, PSE and SCM both use optimisation and simulation. Optimisation, specifically multi-objective optimisation (MOO), was chosen for industrial network analysis as MOO is in line with the top-down, prescriptive approach and able to identify how networks should develop for a given strategy. MOO can further be applied to dynamic networks operating under changing network conditions and can assess network performance with respect to several sustainable development objectives under uncertainty.

Uncertainties can have a significant adverse effect on the operation and therefore environmental, economic and social performance of industrial systems, including industrial networks. The problem lies in the limited ability of industrial systems to respond to changes in the system itself or the system environment, in a manner adequate to maintain the desired performance. Investment in new facilities and new technologies as part of a sustainable development strategy could prove to be costly mistakes if these were to end up as stranded assets because the strategy fails to deliver acceptable performance under somewhat different conditions that the ones expected. Uncertainty analysis tools are therefore included, as the industrial network analysis should have a capability to assess the robustness of its solution. PSE and SCM use similar approaches to eliciting the effect of uncertainty on analysis outcomes. These include stochastic optimisation, interval analysis, but also less common tools like scenario analysis. These are included as it was found that these have capabilities to capture different types of uncertainties.

9.1.2 The Methodology and Case Studies

The industrial network analysis was developed in Chapter 5 and addresses the following challenges:

1. It should elicit the particular issues facing the industrial network.
2. It should identify which strategies are suited to address these issues.

3. It should capture the characteristics that influence structure and behaviour of the network.
4. It should consider environmental, social and economic objectives …
5. … under anticipated future development of the world and …
6. … uncertainty about models and values used.
7. The application of strategies to particular networks provides the challenge of how to adapt or design industrial networks to best respond to these.

The methodology for industrial network analysis proposed in this thesis consists of three parts: an initial problem structuring, subsequent quantitative analysis, and an uncertainty analysis which can be integrated into the problem structuring and quantitative analysis.

9.1.2.1 Problem structuring to engage with contextual complexity

The problem structuring consists of the following five steps:

1. The definition of the problem
2. The definition of the geographical and temporal and network boundary
3. The identification and engagement of stakeholders
4. The choice of objectives
5. The choice of indicators which can be used to capture the performance of the network with respect to these objectives

The problem definition allows the elicitation of the particular issues in light of the influence of the network's socio-political, economic, natural, regulatory environment (addresses challenge 1). The definition of the system boundary includes the identification of existing infrastructure and how this may need to be adapted for the implementation of possible strategies (addresses challenge 2 and to structural characteristics with regards to challenge 3). Stakeholder engagement provides different perspectives and their consultation helps create a more comprehensive picture of the problem and its resolution, but stakeholder involvement can also be used as an opportunity to build consensus about what is to be addressed and the proposed strategy and network development. Objectives, in the context for this thesis, were defined to constitute environmental, social and economic performance. How performance with regards to these criteria is measured and how the success of the strategy will be measured will be determined with the stakeholders based on the particular issues of the network (addresses challenge 4).

The addition of problem structuring stage has three distinct advantages over immediately launching into a quantitative analysis. 1) Various perspectives of the problems are made explicit. 2) Even if influences of the problem context and the network environment are "only" considered qualitatively, the contemplation of the full scope of the situation will beneficially reflect on the subsequent model representation, the way the outcomes are interpreted in the hope of delivering better quality outcomes that are better fitted and reliable for the given context. 3) Problem structuring contributes to the validation of network model by clarifying the issues and making underlying assumptions transparent so that inconsistencies can be readily identified and addressed if necessary.

9.1.2.2 Quantitative analysis of industrial networks

The quantitative analysis developed in this thesis was divided into the following five steps:

1. Scenario generation
2. Data gathering
3. Model development
4. Model execution
5. Identification of preferred network structure and development pathway for the chosen strategy/ies

The *scenario generation* is included in the analysis to consider uncertainty in future developments and events (termed *future uncertainty* in this thesis), as well as uncertainty about, for instance, the indicators included and what is captured in the system boundary (termed *system uncertainty* in this thesis). Scenario analysis serves to find a balance between over- or under-estimating change (Schoemaker, 1995) and guards against common flaws in decision-making such as overconfidence and bias. Scenario analysis is also attractive for the reason that it spreads uncertainty across various scenarios, thereby delivering valuable insights into network behaviour. This addresses challenge 5 and to some extent challenge 6. *Data gathering* is included to give guidance on the level of information detail required and to note parameter uncertainty in this step. The consideration of industrial networks is a multi-scale problem, ranging from processes to economic and political influences. The *model development* captures some characteristics (e.g. stocks, properties of material circulated) while other characteristics may be revealed during model execution (dynamics, network robustness), thereby again engages with challenge 3. There are several approaches to MOO. In this thesis, the ε-constraint method was chosen, an *a posteriori* method. These methods have the benefit that they do not make any value judgements before a solution is chosen. They are more computationally expensive, but they have the benefit that the decision-maker can see what the trade-offs are among the different objectives.

The outcome of the industrial network analysis, i.e. the identification of preferred network structure and development pathway, then addresses challenge 7.

9.1.2.3 Uncertainty analysis framework

The uncertainty analysis framework was developed in Chapter 6 and overlayed the consideration of uncertainty onto the methodology (addresses challenge 6). The consideration of uncertainty is an important part of the industrial network analysis methodology as it may influence whether a sustainable development strategy and network are able to deliver desired performance, and what network structures deliver best performance under this strategy. This is especially relevant for the design of new networks, where decisions have to be made regarding the location, capacity and technologies used in new facilities, and getting these wrong may have costly consequences if these end up as stranded assets. Uncertainty may affect model from, model parameters and empirical parameters, originating from the technical system or value judgements at all stages of the industrial network analysis. The uncertainty analysis framework developed for this thesis is comprehensive and recommends different approaches to elicit the effect on performance and the robustness of network structure for the different types of uncertainties. The framework includes:

- *Scenario analysis* to interrogate future and system uncertainties. This is already incorporated in the deterministic quantitative analysis as it provides insight into network behaviour and as different scenarios may vary significantly in terms of network boundary definition and subsequently in data needs.
- *Uncertainty importance screening* in model and empirical parameters. On the basis of this screening, parameters with insignificant contribution to industrial network analysis outcomes can be dropped from further consideration, potentially reducing the uncertainty analysis effort. However, in the case studies it was found that, if interaction effects are considered, the majority of parameters have significant contributions, i.e. change the outcomes by more that 10% from the expected case.
- *A nested approach* to determining the effect of mathematical expression (through sensitivity testing), model parameter (through interval analysis) and empirical parameters (through stochastic optimisation) on network performance and strategy effectiveness, i.e. ability to deliver good performance. An indication of the robustness of a chosen network structure and development pathway under uncertainty is also intended to be delivered by the uncertainty analysis. It was however pointed out in the second case study that the approach suggested in this thesis has limited ability to deliver a definitive answer as to what ranges of possible performance a specific network structure is able to deliver and that future research may explore the sue of simulation and sampling methods.

The uncertainty analysis has the benefit that it forces the decision-makers to engage in more detail with the network analysis and to be more critical of the underlying assumptions, choices and values.

The application of the industrial network analysis approach to the two case studies has demonstrated that, through the implementation of suitable sustainable developments strategies, network structures and development pathways can be identified that manage to 1) improve performance with respect to sustainable development in existing networks, and 2) promote sustainable development through the design of new networks. A conclusion from dealing with the case studies specifically was that insights about complex industrial systems are obtained as much by dealing with the models, thereby getting a feel for the system, as through the analysis of results. The richness of the system can be difficult to capture in a few graphs and tables. This thesis has therefore demonstrated the ability of the proposed industrial network analysis approach to extend the capacity of analysis tools in IE to capture the complexity of the network context, as well as that of network function and performance for the purpose of evaluating sustainable development strategies and determining preferred network structure and performance.

9.1.3 Benefits and Disadvantages of Industrial Network Analysis

A number of possible benefits of industrial network analysis were identified:

- Apart from identifying network structures and development pathways, industrial network analysis could also be used to assess how an individual facility fits in its surroundings and may strategically position itself in its environment. However, it is not suitable to apply industrial network analysis to a process or facility. Process plants have different characteristics and operate according to purely technological constraints and rules, with none of the complexities that affect industrial networks. Process plants, for instance, have very limited ability to change their structure during their life-time. The analysis also has limited applicability to industrial systems at the level of national or international economies or industrial sectors. The level of aggregation in models on the economic scale would result in the loss of case specific information that would allow tailoring of strategies to the specific needs of similar facilities in different settings.
- A further potential benefit of industrial network analysis could be its use to demonstrate to potential network agents what is required to establish a network, and what the expected performance of such a network would be. For instance, promoting increased material cycle closure could be made more attractive to the involved agents if it is shown how network configuration and operation would look and the environmental and economic potential of sustainable development strategy would be made exemplified. This could encourage the deployment of holistic improvements, rather than partial or “island” solutions (Holweg and Bicheno, 2002).
- Industrial network analysis may also be of interest to the fields of PSE and SCM, as these have to date not extensively engaged with sustainable development considerations in their analysis. Industrial network analysis could be used in PSE, for instance, to a new process plant, should position itself in a network, or if new technologies have a chance of competing with existing ones.

There are also possible disadvantages to the industrial network analysis.

- While it is hoped that the focus on the specific needs of a network will lead to solutions that more effectively address environmental issues and promote sustainable development, the "tailoring" of analysis does introduce a degree of subjectivity to the analysis. There is no one set of indicators or a specific network definition that would ensure a consistent approach for different cases, as there is for instance in LCA. Should the industrial network analysis be repeated for the same or a similar network with a different set of stakeholders and decision-makers, then the analysis may lead to different outcomes. However, the question is whether different outcomes equate to one outcome being worse or better than another. As long as there is a net benefit by instituting sustainable development strategies, then that strategy is still acceptable.
- While the industrial network analysis approach, with the description of the sustainable development context and its characterisation of networks, has engaged with system complexity, there is scope to take more of this complexity on board in the quantitative analysis. The approaches used here do not use the most sophisticated analysis approaches available, primarily due to computational limitations. Future work could for instance include stochastic processes to consider the effect of fluctuating parameters. Multi-stage stochastic optimisation could be used to more realistically represent multiple decisions taken over time.

9.2 LIMITATIONS OF INDUSTRIAL NETWORK ANALYSIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

9.2.1 Consideration of Operational Performance

An important aspect that could not be considered in this thesis is the influence of sustainable development strategies on the day-to-day operation of the networks. If any of the strategies are to be implemented in practice, it has to be considered how the daily operations are affected if changes such as increased material reintegration or new technologies are introduced. Facilities would for instance be required to manage raw material stocks differently if the raw material delivery would show a greater variability in quality and timing of delivery. The processes may have to be adapted to cope with this change in raw material quality. Information would have to be more easily accessible and more widely distributed in a highly interconnected network because greater interconnectivity would require greater team work to ensure continued smooth operation and the prevention of disturbances spreading throughout the network.

The possibility of capturing industrial networks in greater detail was briefly mentioned in the discussion of multi-level modelling in Chapter 4. In this regard PSE and SCM also provide sources of valuable information, especially as the importance of operational issues on wider system planning have been recognised in these fields. In several instances process design has compromised supply chain operation (see, e.g. Shah, 2003). Backx, Bosgra, and Marquardt (1998) therefore introduce the concept of supply chain conscious process operation and process design for supply chain efficiency is seen as an important future research area (Shah, 2005). PSE for instance offers the concept of system control, which is intended to keep all parts of the system operating within certain performance margins, ensuring the process can continue to operate adequately and safely. However, the same degree of tight control may not be possible or even desirable for an industrial network, where emphasis is more on maintaining flexibility to be able to respond to changes, rather than attempting to eliminate disturbances. In SCM, therefore, the coordination of suppliers and customers and the associated information management has received much attention (e.g. Themistocleous et al. (2004), Humphreys et al. (2001), Shaft et al. (2002)). Humphreys et al. (2001) for instance address how to deploy inter-organisational information systems.

The development of models which integrate models at multiple system levels (e.g. process models embedded in network models) are at an early stage. However, this form of modelling would also be attractive for industrial network analysis, for instance to embed detailed process models in meta-models of the network, or to link models of the environmental to the industrial network model. To handle these problems requires flexible modelling environments that can handle a greater variety of models. This shift will result in more complex models.

9.2.2 Lacking Consideration of Agent Behaviour

There are some limitations to the use of industrial networks analysis as conceived of in this thesis. The analysis does not explicitly take into consideration **agent interest or behaviour**, although it can be argued that assumptions such as unwillingness to invest in unprofitable technologies are already considerations of agent behaviour. Alternatively, the optimisation of the network can in effect be seen as the ideal network configuration for an agent that has a) the interest in getting the best results out of the overall system, rather than particular units, and b) a level of control (or the dominance to effectively have the control) over the entire system to be able to implement such a global optimum. While the absence of an explicit consideration of agent heuristics can be seen as a limitation, there is also benefit to knowing what is technically achievable without the constraints of agent interest.

9.2.2.1 *Bottom-up: Complimentary Approach to Industrial Network Analysis*

While only simulation and MOO are considered explicitly in this thesis, other modelling approaches, such as system dynamics or agent-based modelling could also be used. However, the use of these modelling approaches would change the focus of the analysis to a bottom-up description of how industrial networks evolve, rather than prescribing how they should develop. Nevertheless, these modelling approaches are of interest to industrial network analysis as they can explicitly account for the social dimension and thereby consider the viability or success of strategies and policy instruments, provided the underlying assumptions of agent behaviour are accurate. In other words, the top-down approach proposed in this thesis is not deemed preferable or intended to replace the bottom-up, agent based approach. Rather, the two approaches should be seen as complimentary.

Strategy development could be facilitated through a dual approach (Figure 9-1): Global optimisation models (where ‘global’ refers to optimising the overall network in its entirety, without trading off between the individual agent objectives) help to determine the preferred sustainable development pathways, which become the strategy goals. The effectiveness of various individual or mixed policy incentives in encouraging system evolution in that direction are then interrogated through the use of, for instance, agent-based modelling (ABM). The former takes the viewpoint of a global decision maker that wishes the best outcome for the system. The latter takes the distributed nature of agent control into account. These two approaches can therefore also be referred to as *global and distributed control approaches*. A model of industrial networks that assumed top-down takes limited consideration of individual agent objectives, instead focusing on what is technologically feasible and preferable in terms of global performance. Bottom-up models are in turn be used to determine what barriers exist to reaching the identified policy goal and what outcomes are feasible, by fully accounting for business decision making, agent perspectives and values. Various policy interventions could be explored in terms of their effectiveness in moving the industrial network towards the desired goal.

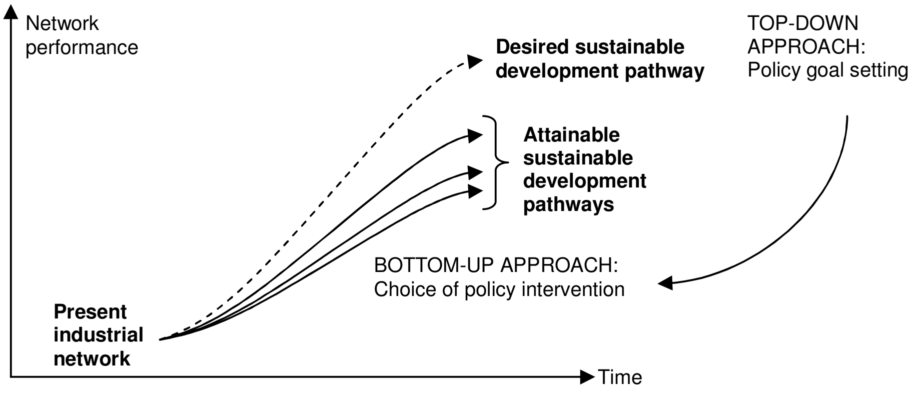

Figure 9-1 Global and bottom-up approaches: The former can determine preferred states, which in turn informs the policy interventions that can be explored for effectiveness in bottom-up models (Beck et al., 2007b)

Figure 9-2 illustrates the difference between the two approaches, which can be explained in terms of cause/effect relationships and system interactions. "Causes" encompass any change to the system condition, whether this stems from policy incentives, price developments, or decisions around structural changes. The "effect" is the resulting network evolution.

The top-down approach, which could also be described as assuming overarching global control, is focused on attaining a desired *effect*; in other words, a preferred operational and structural network development based on given objectives. By making assumptions about network structure and behaviour, opportunities for change, or causes, can be identified through optimisation that moves the industrial network development as close as possible to the desired state. The extent to which the desired effect can be achieved is dependent on the industrial network and the environment within which it is embedded. Existing network infrastructure imposes, amongst others, technological and economic constraints, and only limited opportunities may be available to overcome these.

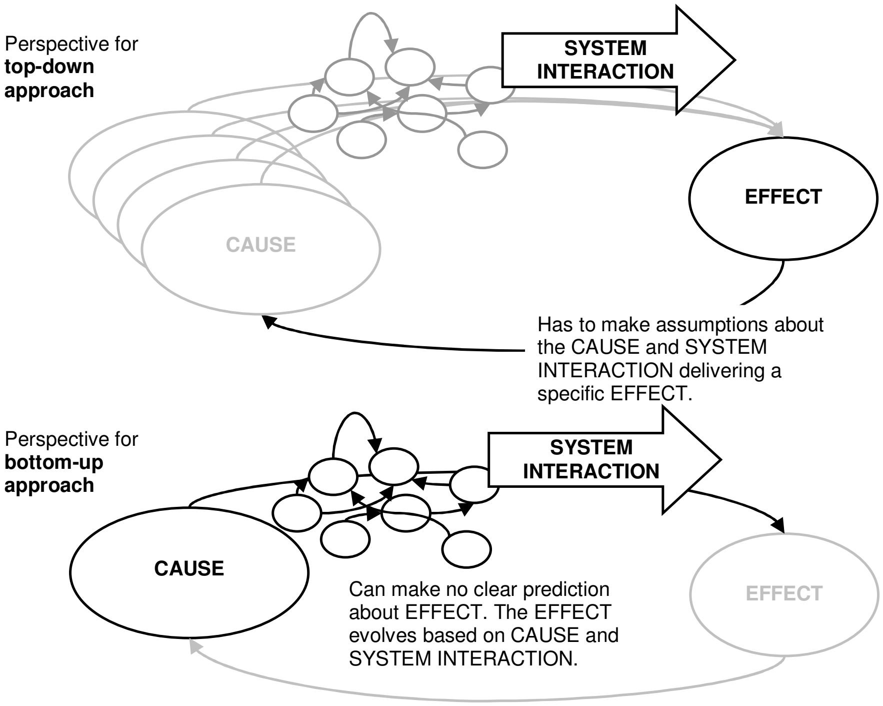

Figure 9-2 Illustration of the difference in approach between the global and bottom-up models.

The outcome of the top-down network assessment provides a point of reference for the assessment of behaviour and evolution of industrial networks under strategies interventions, both monetary as well as non-monetary. The disadvantage is that it can be difficult, if not impossible, to tell what effects will be achieved, due to the complexity of the agent interactions and distributed control by several agents of an industrial network.

10

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