A New Model for Assessing Sustainability of Complex Systems

Integrating LCA and RA for Sustainability

Gayathri Babarenda Gamage

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Civil and Environmental Engineering

The University of Auckland, 2011

ABSTRACT

Assessment of sustainability is an essential step in determining if action taken is sustainable. Early research in sustainability assessment was based on reconciling the three pillars (environmental, economic and social) using the weak sustainability model. Today there are numerous indicators (single and composite) for measuring impacts in the three systems (environmental, economic and social) using the strong sustainability model where current thinking emphasises the need for system thinking rather than the reductionist concept of pillars. Most existing indices/methods measure single aspects of sustainability and the more integrated indicators are aimed at national or global level assessments.

A review of existing indicators, methods and models within the context of complex system sustainability showed that no single existing index, method or model was able to assess sustainability of complex systems since most fail to account for complex system characteristics such as system dynamics, interconnections and interdependencies of system components, system's ability to learn and remember, emergence of novel behaviours, co-evolution, etc. However, two analytical methods, Life Cycle Assessment (LCA) and risk assessment (RA), were found to have significant potential for addressing concerns regarding sustainability of complex systems as they were able to account for complex system characteristics. Thus LCA and RA were integrated in a new model to assess sustainability. The model is tested on case study product systems to illustrate applicability, potential issues and areas for improvement.

AKNOWLEDGEMENTS

With gratitude I acknowledge my academic supervisor, Associate Professor Carol Boyle, for her helpful guidance, valuable insight as well as for furthering my interest in sustainability. Thanks also to my co-supervisor Dr. Ir. Ron McDowall for your support. Many thanks to my advisory committee members: Dr. Rainer Seidel and Prof. Bruce Melville from the University of Auckland; Mr. Jake McLaren, my company advisor and Environmental Manager at Formway, for your support, friendship and valuable insights; and Mr. John Gertsakis. I am grateful to Technology New Zealand for the financial support for this research (Technology Industry Fellowship grant no.FMYX0506). Thanks also to Dr. Sarah McLaren and Dr. Barbara Nebel for helpful insights on LCA studies.

Thanks are due to the many Formway staff members for your knowledge, input and support while I was conducting my case study research in Wellington. Special thanks to Formway's R&D staff (former and current): Bob Stewart, Mark Pennington, Ed Burak, Damon Burwell, Paul Wilkinson, Ian Footit, Mike Francis, Sonia Guild, Peter Osbourne, Damon Boswell, Kat, Greg Smith and any others who I've been privileged to interact with, for their help during my work and for showing me true teamwork in practice. Special thanks to Jon Prince, my former mentor at Formway design studio for your humour, leadership and unfaltering faith in my abilities. Many thanks also to Peter van de Laar for your helpful knowledge and input on Formway processes.

My sincerest gratitude to my parents for their support– I am indebted to you forever for your love, the many lessons in life and values you have taught me. My brother Prasad and sister Dinesha have been supportive through the years. The Ranasinghe family, who became my second family while I was based in Wellington, thank you so much. I would also like to thank my dear friends and fellow doctoral candidates Dan, Idil and Jeff who were supportive throughout the PhD process, a great source of inspiration, strength and laughter. I'd like to thank Roger for brightening my days and Vanessa for her friendship. Lastly, I would like to dedicate this to the memory of my grandparents.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CAS	Complex Adaptive Systems
CBD	Convention on Biological Diversity
CSR	Corporate Social Responsibility
CBA	Cost-Benefit Analysis
CNC	Critical Natural Capital
EF	Ecological Footprint
ESD	Ecologically Sustainable Development
EWI	Ecosystem Wellbeing Index
EDIP	Environmental Design of Industrial Products (Denmark)
EIA	Environmental Impact Assessment
EPI	Environmental Performance Index
ESI	Environmental Sustainability Index
FCA	Full Cost Accounting
FCEA	Full Cost Environmental Accounting
GPI	Genuine Progress Indicator
GRI	Global Reporting Initiative
GWP	Global Warming Potential
GHG	Greenhouse gas
GDP	Gross Domestic Product
HDI	Human Development Index
HWI	Human Wellbeing Index
IFOTIS	In Full, on Time and in Spec
ISEW	Index of Sustainable Economic Welfare
IDEMAT	Industrial Design Materials
IPENZ	Institute for Professional Engineers New Zealand
IPENZ	Institute of Professional Engineers of New Zealand
IPCC	Intergovernmental Panel on Climate Change
IISD	International Institute for Sustainable Development
IIDEX	International Interior Design Exposition
IUCN	International Union for the Conversation of Nature
LCCA	Lice Cycle Costing Assessment
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LPI	Living Planet Index
MCA	Multi-Criteria Analysis
NGO	Non-governmental organization
PFC	Perfluorocarbons
PPP	Policies, Plans and Programs
PSI	Product Sustainability Index
REPA	Resource and Environmental Profile Analysis

RA	Risk Assessment
SELCA	Social and Environmental Life Cycle Assessment
SLCA	Social Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SEA	Strategic Environmental Assessment
SAFE	Sustainability Assessment by Fuzzy Evaluation
SPI	Sustainability Performance Index
SD	Sustainable Development
TNS	The Natural Step
TCA	Total Cost Assessment
TBL	Triple Bottom Line
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNGA	United Nations General Assembly
WCED	World Commission on Environment and Development
WWF	World Wildlife Fund

CHAPTER 1: INTRODUCTION

Currently, the world population stands at approximately 6.8 billion people according to the US Census Bureau (2010). This figure is expected to increase to around 9 billion in 2040. In most parts of the world, births outnumber deaths. While it might be considered a sign of a thriving civilisation, we know that many people are facing a myriad of issues and this would only worsen if left unaddressed. Examples of the issues faced include climate change, loss of biodiversity, pollution, poverty, etc. The impacts of these issues are likely to increase with increased population as more and more people compete for finite resources, putting more pressure on earth's systems.

Within our civilisation, there are three interconnected and interdependent systems: the environment which includes all earth's systems, society which includes humans, how they live and interact, and the economy which has become the cornerstone of trade and commerce. Today we depend on the economy for individual well-being in terms of goods and services to enhance lives. The economy is based on consumption of resources, a system by which individual businesses and countries trade with each other. Employment in businesses provides individuals with income which they then use to gain material consumables, services and experiences which are meant to enhance quality of life. Thus society depends on the economy, the economy depends on the environment for resources, and society also depends on the environment for health, resources, etc. While the environment does not need humans for it to function, human actions play a significant part in its wellbeing. The three are so interconnected that it is virtually impossible to address one without affecting the others. There are limitations in each system as the Earth is a finite entity. We have been lucky so far in that the dynamic interactions between the three have maintained some semblance of balance, however, there is evidence that this balance is deteriorating.

Environmental degradation back in the 1960s sparked what may now be identified as the beginning of 'environmental activism'. The activities raised awareness of environmental issues, however, generated few solutions; and as such, the same problems that existed then continue to plague us today, but with more urgent need for solutions. A number of books on the state of the environment such as 'Silent Spring' by Rachael Carson (Carson, 1962), 'The Limits to Growth' by The Club of Rome (Meadows et al., 1972) and 'Small is Beautiful' by Schumacher

(Schumacher, 1973) were among popular literature at the time and encourage on-going debate regarding the future well-being of the planet. The concept of limits, introduced by Forester (1971) and Meadows et al. (1972) debated that once we have reached the limits to growth, industrial capacity would decline together with population. Critics such as Cole et al. (1973) replaced Meadow's original assumption on absolute resource limits by accounting for discovery and recycling, thus prolonging the fatal collapse. Others such as Craig (2001) argued that present systems are far from reaching limits - "given available energy, there is no concentration limit on sustainability" (Craig, 2001). It is apparent that the positive effects of globalisation and technological innovation, among other developments, have been successful in extending limits.

According to Hirsch (1976), social limits are of immediate concern as opposed to environmental concerns. Indeed, there is evidence that society is very sensitive to limitations, as witnessed by conflicts including recent ones involving Israel-Palestine-Lebanon, Ethiopia-Somalia, Rwanda, Zaire, Afghanistan-USA, Iraq-USA, etc. (King-Irani, 2007; Blinc et al., 2007; etc.). Evidence in terms of conflicts is not necessary to deduce that, while most conflicts have a political front, limitations in terms of inequality related to environmental and economic resources are one of the underlying drivers (Klare 2001; Anderson, 2003; Martin et al., 2006). Thus it is fairly difficult to identify and tackle problems for sustainability by concentrating on any one of the traditionally compartmentalised (environmental, societal and economic) views. Additionally, due to the complex interconnections between the three systems as given either by the weak or strong interpretations of sustainability, it is argued that all three must be taken into account when taking actions (Davidson, 2000; Ayres et al., 2001; Bebbington, 2001; etc.). Today, as in the 1960s, there is a constant supply of entertaining literature warning of the dire consequences for humanity should we fail to act in time (Diamond, (2004), Wright, (2005), Kunstler (2005), etc.), but few outline how to deal with the problems in a practical manner.

Many (Brundtland Report (WCED, 1987), Intergovernmental Panel on Climate Change reports (e.g. IPCC, 2001, etc.), Global Environmental Outlook reports (e.g. UNEP, 2002, etc.), The Stern Review (Stern, 2007), etc.) have established that the human race is heading towards major difficulties pertaining to two issues:

1. The inequality forced upon the world's poor in terms of meeting needs (water, food, shelter, etc.); and
2. The environmental degradation forced upon the earth both by the developed and the developing world.

Even though the word 'sustainability' can now be accounted as a common slogan, the concept has yet to prevent society from pursuing economic prosperity while disregarding environmental and social welfare. This economic prosperity is related to consumerism, which is driven by humanity's quest for material goods. Note that the definition for consumerism for the context of this research is taken as the consumption of goods as a means for improving the economy (Cravens and Hills, 1970; Kaufman and Channon, 1973). Likewise, the definition for materialism is taken from Belk (1984) as "the importance a consumer attaches to worldly possessions". Materialism and consumerism have their respective advantages and disadvantages in society (Packard, 1961; Lintott, 1998); one advantage is that they fuel the economy, enabling employment and providing for needs. A certain amount of materialism is required for our day-to-day survival, both in terms of biological and sociological survival. The disadvantages include a cycle of increasing resource consumption and environmental degradation while doing very little to alleviate poverty (Jackson, 2000).

This is where this research comes in. This thesis is based on the problem of un-sustainability, in particular that which results from industrial activities, namely design and manufacture of products. We humans have grown increasingly dependent on technology and products for our wellbeing and survival. The manufacture of products to supply the demand is the construct of our economy, where these goods have been given economic value. Common sense says that the more goods a manufacturer can sell, the more the profit. The problems occur when the manufacture of goods, which require inputs from the environment, result in adverse impacts that go unchecked and unmitigated. Development that is sustainable should be capable of helping humanity achieve goals while safeguarding the environment for future generations. Thus far most manufacturing operations may be unsustainable in the long term.

Putting the concept of sustainable development into operation has long been the focus of many governments, organisations and institutes. Nevertheless, in practice, the concept of sustainable development has been an ad-hoc process at best. The steps taken, while done with the best of intentions, do not necessarily guarantee that designs, developments, products, etc. are in fact going to be sustainable. It is safe to say that almost all manufacturing results in some form of adverse impact. The cumulative effect of these adverse impacts can cause harm at both a local and global level and there are many examples ranging from melting of glaciers to species extinction. There are many measures that companies can take to minimise impact. Likewise, there are many methods, models and tools available to determine what the impacts are. The information from finding impacts can be useful to help identify specific problems and hence address pressing issues. One of the areas that are lacking is the assessment of sustainability.

Decision-makers and policy-makers rely on information to make good decisions and policies. The results of assessments are one way of obtaining the required information. In a way, the provision of information can help the resilience of a system as decisions can be made to prevent the system from collapsing. There are many types of existing sustainability assessments, some that use indicators and others that are highly qualitative and principle based. It is not clear how these existing methods and models account for the complexity of the systems they assess and whether they actually assess sustainability. Part of this research is based on evaluating existing methods and models for assessing sustainability within the context of complex systems.

1.1 OBJECTIVES

The primary objective of this research is to develop a model to assess sustainability applicable to product systems, incorporating entities significant to the concept of sustainability. The sub-objectives are as follows:

1. Review existing models and methods to determine if they assess sustainability;
    - Determine what methods and models exist for assessing sustainability;
    - Identify strengths and weaknesses of the existing methods and models;
    - Determine the basic criteria required for sustainability and hence determine whether the existing methods and models assess sustainability;
2. Develop a new model to assess sustainability by integrating existing methods and models;
    - Integrate the most appropriate existing models in order to capitalise on their strengths, minimise individual weaknesses and also meet the criteria for sustainability; and
3. Test the new model on case studies;
    - Use the new model to assess systems within business to determine whether the model can practically assess sustainability.

1.1.1 OUTCOME OF OBJECTIVES

This work is based on developing a sustainability assessment model that is capable of assessing sustainability of complex systems. In doing this, a number of fields of research, such as those pertaining to complex systems and sustainability assessment, are reviewed to determine criteria for sustainability of complex systems. The direct outcomes of the objectives include:

- Identification of criteria required for assessing sustainability;
- Evaluation of existing sustainability assessment methods and models to determine whether they are able to assess sustainability of complex systems;
- A new model to assess sustainability by integrating existing models and methods that would be able to:
    - Identify weaknesses in the system in terms of environmental hotspots; and
    - Identify critical risk to the system and how they affect sustainability of the system;
- Case study results on application of the model in the office furniture industry (based in New Zealand); and
- Recommendations on addressing and managing risks and opportunities to assist sustainability.

One of the significant, though indirect, results of the research includes some insight on how risk relates to sustainability together with the significance of risk perception and decision making for resilience and sustainability.

1.2 RESEARCH SCOPE

Sustainability is a broad field of research encompassing many and all activity involving environmental, social and economic systems. This is to say that the scope of sustainability issues is limitless. While it is difficult to restrict a study with the word ‘sustainability’ in it, this research is narrowed down in a number of ways while attempting to preserve the holistic nature of the sustainability concept. Therefore the scope of the research can be categorised into two separate scoping fields according to theoretical inquiry and practical implementation. This scope is similar to the system boundaries applied to the developed model itself (given in section 5.3.1) and spans over environmental, social and economic systems in general. The application of the model for this research is based on assessment of product systems, which is embedded within the economic system via business.

1.3 CONTRIBUTION TO KNOWLEDGE

A number of studies developing models for assessing sustainability already exist in literature. The novelty of this research is in the integration of existing methods and models such that an attempt to assess sustainability, by taking all significant dimensions of sustainability from a complex systems context, is made. The thesis thus contributes to knowledge in a number of areas as follows:

1. Identifies criteria for complex system sustainability;
2. Develops a new model to assess sustainability of a complex system to provide for the identified criteria; and
3. Application of the new model on case study product system.

There are also numerous indirect, yet significant, contributions in the form of critiquing the model in terms of improvements as well on how to practically influence change for sustainability of the product system and overall complex systems. The link between risk and sustainability is explored in terms of decision making for risk mitigation, prevention of unsustainability and thus continuity of a product system.

1.4 SUMMARY OF CONTENT

This thesis has eight chapters from Introduction to Conclusions. The content of each chapter is summarised:

Chapter 1 – The chapter starts with a basic outline of the issues leading to the need for sustainability, some of the existing issues, scale of the issues facing humanity, etc. It also consists of the objectives of the research, the scope and outline of the contribution to knowledge.

Chapter 2 – The first part of the chapter reviews literature on complex systems, complex adaptive systems and characteristics of these systems. The second part identifies and reviews existing sustainability assessment methods and models.

Chapter 3 – Consists of identifying characteristics of complex systems that form the criteria for sustainability assessment. The chapter evaluates the existing sustainability assessment methods and models reviewed in Chapter 2 resulting in a number of existing methods and models that have the required characteristics needed for assessing sustainability of complex systems.

Chapter 4 – Evaluates the resulting methods and models from Chapter 3 to narrow down on two existing methods, LCA and RA, which when integrated, would be able to assess sustainability of complex systems.

Chapter 5 – Analyses existing attempts at integrating LCA and RA in order to determine how best to integrate the two for the purpose of sustainability assessment. The chapter presents the new model for assessing sustainability of complex systems.

Chapter 6 – Consists of case study results when the model is applied to assess a product system. The results including two risk matrices with evaluated risks are discussed with respect to their significance for sustainability.

Chapter 7 – The model is critiqued with respect to where it succeeds and where improvements can be made. Decision making for sustainability using risk is also explored.

Chapter 8 – Conclusions and future work.

1.6 THE LITERATURE

The theoretical scope of the thesis is based on the development of a model and determining if and how the components of the model are significant for sustainability while maintaining practicality. This is essentially the scope of the literature reviewed. Since the theories pertaining to methods and models in the field of sustainability are many, the most well-known ones are reviewed. This confines the theory to that involving environmental assessment, sustainability assessment, sustainability from a manufacturing context, sustainable development from a business perspective, sustainable development from a principle based perspective, the development of individual methods and models (LCA and risk assessment), their properties, methods and use. These elements cover a wide range of principles and methods which are described and critiqued in Chapter 2: Literature Review.

The research reviews two main streams of literature: 1. Literature on complex systems; and 2. Literature on sustainability assessment methods and models. The first part of the review outlines the concept of systems, particularly complex systems which comprise of a multitude of Earth's systems. The theory and practice in the fields of complex systems and resilience are briefly outlined. This is necessary to ensure significant components of sustainability are identified for the model developed during this research. A number of widely accepted and used sustainability assessment methods and models are then reviewed to identify their strengths and weaknesses and to show the current status of development in sustainability assessment literature. The methods and models are categorized and reviewed according to whether they contain criteria/principles for sustainability or are tools which give the user step by step instruction on how to assess sustainability.

1.7 PUBLICATIONS

A number of publications at conferences and journal papers have resulted from this thesis:

- Babarenda Gamage, G., Boyle, C. and McDowall, R. (2010) The Development of an Integrated Model for Assessing Sustainability of Complex Systems, 4th International Conference on Sustainability Engineering and Science, Auckland, NZ, Nov 30- Dec 3, 2010.
- Babarenda Gamage, G. and Boyle, C. (2008) 'Sustainable development: a review of progress, stagnation and potential', *International Journal of Sustainable Development,* Vol. 11, No. 1, pp.45–60
- Babarenda Gamage, G., Boyle, C., McLaren, S.J. and McLaren, J. (2008) Life cycle assessment of commercial furniture: a case study, *International Journal of Life Cycle Assessment*, 3:401–411
- Babarenda Gamage, G. and Boyle, C. (2007) Sustainability through Risk assessment: A Case Study of resource risk, Proceedings of the 2nd International Conference on Sustainability Engineering and Science, Auckland, NZ, Feb 21-23, 2007.
- Babarenda Gamage, G. And Boyle, C. (2006) Developing the use of environmental impact assessment in commercial organisations: a case study of Formway furniture. Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, May 31–2 June, 2006.

CHAPTER 2: LITERATURE REVIEW

Fiksel (2003) states that “the concept of “sustainability” is often associated with resource constraints and maintenance of status quo rather than with opportunities for continued innovation, growth, and prosperity”. Even though the need to reconcile socio-economic development and Earth’s limitations had been identified since the beginning of the environmental movement, research was focused on understanding and solving individual problems in a Newtonian manner. The attempts to solve problem linearly led to some understanding of problem complexity, fundamental questions regarding the problems, as well as understanding that targeting problem-driven research was insufficient for sustainability (Clark and Dickson, 2003). Therefore, research towards understanding sustainability in terms of complex systems considering multiple perspectives, dimensions and disciplines is currently being considered with the expectation that understanding the intrinsic complexities would give rise to novel solutions. Understanding of resilience and other significant system characteristics is required within these novel approaches.

2.1 SUSTAINABILITY, SYSTEMS AND RESILIENCE

Work done by engineers and scientists, termed “hard science”, mainly takes on a functionalist systems approach which is based on Newtonian and Cartesian principles where the whole is considered as the sum of its parts. This view simplifies systems by considering them as deconstruct-able hierarchical entities which can then be modelled linearly via a series of equations (Sawyer, 2005; Rihani 2002). This method of analysis is useful for quantifying problems and optimizing solutions individually as parts. However, it over simplifies the complexities arising from human-social interactions. One success story where a functional systems approach to sustainability has been used is the case of Interface Carpets where goals for sustainability have been converted into functions within the business system (Rosenberg, 2005) and implemented top-down.

In contrast to functionalist system theory is interpretative system theory which is based on the idea that the whole is greater than the sum of its parts (Hammond, 2003). According to Hatch and Yanow (2003), the theory considers systems as mental constructs of observers thus the ideas of the observer are significant. The interpretative system approach is based on self-understanding where understanding depends on self-awareness and reflection of other systems thus is highly subjective. The advantages of the approach are in communication of ideas, awareness, engagement of stakeholders, critical thinking and ethical action based on self-fulfilment (Bausch, 2001; Bradbury 2003). The major disadvantage of this approach is that the collaborative approaches taken may not lead to sustainable solutions and may in fact lead to the opposite or inaction.

Complex system theory stemmed from quantum mechanics principles and according to Sawyer (2005), a complex system consists of large populations of independent, interacting and self-interested agents where behaviour of the whole cannot be explained by the behaviour of the individual parts. The main characteristics of a complex system are self-organization (Nishiguchi, 2001), emergence (Rihani, 2002; Porter, 2006) and change. Examples of complex systems include the weather, political parties, stock market, etc. (Nonaka and Nishiguchi, 2001; Gell-Mann, 1994).

From complex system theory stemmed Complex Adaptive System (CAS) theory which included work by Jantsch (1980), Gell-Mann (1994), Holland (1995), Maturna and Varela (1992), and Prigogine and Stengers (1984), etc. A CAS is a system where emergence or the multitude of various interactions within the system leads to increased chance of survival. Dooley (1996) provides a nominal definition of CAS including properties. Examples of CAS are the human immune system (Holland, 1992; Levin, 1999) and economic markets (Markose, 2005).

The Earth as a system can be considered as a CAS (Holland, 1995; Norberg and Cumming, 2008). Within the Earth system are a multitude of other complex systems, most of which interact with humans and are also subjected to human activity. Organisations are systems within the Earth system and can be classified as complex adaptive systems as they exhibit the characteristics of complex systems, which according to Waldrop (1992), include the presence of multiple independent yet interacting agents, systemic interactions leading to self-organisation and learning via feedback. However, management of an organisation can be comprised of a mix of formative, informative or complex system theory or a combination of the three at appropriate times. Many researchers have acknowledged the need for systems thinking in order to understand complexity and hence tackle issues regarding sustainability (Hürlimann, 2009; Martin, 2002; Checkland, 1999; to name just a few).

2.1.1 RESILIENCE, COMPLEX ADAPTIVE SYSTEMS AND SUSTAINABILITY

The field of ecology has seen many works on resilience and today there are two major streams of research which have extended to other disciplines including engineering. One stream of research develops heuristic models to better understand system resilience considering human social and economic activities while the other attempts to gain better understanding of ecosystem resilience and biodiversity with empirical data and modelling. Resilience is no longer only limited to ecology and can be used to understand any type of system according to different disciplines. Holling (1973) defined ecological resilience as “A measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures.” Then in 1996, Holling defined engineering resilience as “the rate at which a system returns to a single steady or cyclic state following a perturbation” (Holling, 1996). Of the two types of resilience, static and dynamic, the Earth systems fall under dynamic resilience with multiple states of equilibrium (Kauffman, 1995).

The adaptive cycle is a significant characteristic of CAS. The idea of adaptive cycles resulted from research on heuristic models (Holling, 2001). An adaptive cycle describes the process of development and decay of a system and contains within it four phases – exploitation (r), conservation (K), release (Ω), and reorganization (α) (Holling and Gunderson 2002). This work also outlines three properties of an adaptive cycle:

1) Inherent potential for change;
2) Internal degree of connectedness, flexibility, or rigidity; and
3) The adaptive capability or resilience of the system.

Figure 1, from Holling et al.’s (2002a) book Panarchy: Understanding Transformations in Systems of Humans and Nature, shows the most important adaptive cycle in terms of sustainability where sustainability is defined as “the capacity to create, test and maintain adaptive capability”. The word “panarchy” was coined to represent the nature of adaptive cycles which are nested hierarchically within each other (Holling, 2001; Gunderson and Holling, 2002). According to Levin (1998), complex systems are resilient as they resist change or change slowly. Basically, a system maintains stability because it is protected by slow conservative changes in larger systems above it, while being energised by faster changes in smaller systems below it. Critical conditions within levels can cause disruptions between levels and destabilise the system. The “revolt” and “remember” cycles are significant at times of change. “Revolt” occurs at the Ω phase where a level in the panarchy experiences a collapse. The cascading effect can cause disruptions to larger and smaller levels triggering a crisis. The “remember” cycle draws information, energy or resources from the slow and larger levels to facilitate renewal.

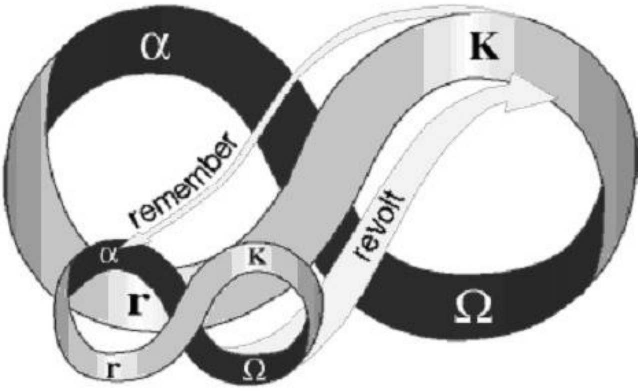

Figure 1: Panarchy – revolt and remember cycles (Reproduced from Holling et al., 2002a)

According to Carpenter et al. (2001), a resilience of systems can be defined by:

1. “The amount of change the system can undergo and still remain within the same domain of attraction;
2. The degree to which the system is capable of self-organisation; and
3. The degree to which the system can build the capacity to learn and adapt”

Furthermore, complex systems are said to be continuously evolving. This is in contrast to engineering systems which are mainly thought of as static. Internal and external perturbations are said to cause a system to reach critical thresholds after which the system reorganises (Holling 1973; Scheffer and Carpenter, 2003). Resilient systems have a higher capability for self-organisation where function is distributed “within and across” the system (Garmestani et al., 2009). Thus if a component of the system fails, the function would still be preserved. It is necessary to understand the interactions between and within systems to increase resilience and capability to adapt (Walker et al., 2004).

Environmental damage undermines system health by reducing resilience and increasing vulnerability (Munasinghe and Najam, 2007). Regime shifts are said to occur when system resilience has been reduced by the removal of diversity and components of the system that are capable of maintaining certain functions (Folke et al., 2004). The idea of a threshold in preventing catastrophic system collapse has been discussed earlier on by Holling (1986); however, there are issues with uncertainty in predicting thresholds.

One of the criticisms regarding the adaptive cycle comes from Abel et al. (2006) who argue that the phases do not occur in the order proposed. This is acknowledged to some extent by Holling and Gunderson (2002). Abel et al. (2006) have found evidence of cross-scale effects which occur outside the “revolt” “remember” cycle. One example of this is government intervention leading to system collapse. Furthermore, there is consensus that the four-phase adaptive cycle is not universal across systems. Another, and perhaps more significant criticism comes from Janssen et al. (2006) who say there is no simple relationship between connectivity and resilience as given by Holling and Gunderson (2002). In addition, the literature related to panarchy and resilience does not seem to consider population growth, social and political conflict, the effects of social elites, etc. all of which are significant factors in organised human social systems (Gotts, 2007). Nevertheless, the adaptive cycle denotes change which is a significant characteristic of systems.

Research in sustainability has been based on development of tools and criteria to determine what constitutes as a sustainable system such as an organisation. Munasinghe (2001) noted that there has been a distinction between sustainability literature in developed and developing regions. The developed nations have focused on growth, population increase and pollution while poverty, equity, economic development, etc. have been the main focus of developing regions. A review of sustainability paradigms considering a number of broad perspectives including the psychological and business facets, progression as a theoretical and a practical concept, as well as the subject of heightened materialism and consumerism resulting in current adverse trends is discussed in Babarenda Gamage and Boyle (2008).

While there is on-going research based on addressing environmental issues, though in a more integrated manner with social and economic issues, recent research has been focused on analyzing resilience for transitioning towards sustainability (Folke et al., 2002; Folke, 2006). As such, not only is there a growing body of literature in ecological economics which attempt to combine ecological and economic methods to find solutions to environmental problems, but there is consensus that systems thinking, modelling complex system behaviour to gain better understanding of sustainability as well as multidisciplinary approaches are required for sustainability (Ehrenfeld, 2003; Fiksel, 2003: Fiksel, 2006; McMichael et al., 2003; Graedel and Klee, 2002).

Technology has played a significant part in human interaction with Earth systems. As such, the significance of innovation and transition to sustainability has been a focus of much research effort (Kemp, 1994; Geels, 2005; Tukker et al., 2008) where function and change of systems are being investigated in an attempt to answer questions regarding how systems emerge, how and why transition occurs as well as sustainability in production and consumption. According to Teisman and Edelenbos (2004, pp176), “transition [in systems] result from unordered and chaotic processes, partly created through management but also born from coincidence”. Understanding transition could be vital to influence transition to sustainability. Human organisation and management that is mindful of complexity is seen as a necessity to understand problems encountered by organisations and Earth systems and as such, there is a growing body of literature in the area of leadership taking account of complexity (Snowden and Boone, 2007; Lichtenstein, 2007; Plowman et al., 2007). Furthermore, sustainability science has emerged from the need to integrate knowledge in multiple disciplines with the overarching goal of studying interactions between human and natural systems (NRC, 1999; Schellnhuber et al., 2004; Mihelcic et al., 2003)

2.2 SUSTAINABILITY ASSESSMENT

Devuyst (2001) defines sustainability assessment as “a tool that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society more sustainable”. Pope et al. (2004) defines sustainability assessment “as a process by which the implications of an initiative on sustainability are evaluated, where the initiative can be a proposed or existing policy, plan, programme, project, piece of legislation, or a current practice or activity.” In short, the purpose of sustainability assessment is to “minimise unsustainability” (Pope et al., 2004).

According to Onisto (1999), one of the outcomes of Agenda 21 (UN, 1992) was the development of methods, models and indicators for sustainability assessment. Concepts of sustainability can either be incorporated into existing environmental impact assessment (EIA) applicable to projects, strategic environmental assessment (SEA) applicable to policies, plans and programs (PPP), or developed as separate systems (Devuyst, 2001; Buselich, 2002; Therivel and Partidario, 1996). Development of impact assessment approaches based on EIA and SEA approaches have been documented by many researchers including Saddler (1999), Gibson (2001), Verheem (2002), etc.

Pope et al. (2004) highlights existing approaches to sustainability assessment, categorising them into EIA-driven integrated assessment and Objectives-led integrated assessment where social and economic components have been integrated to EIA and SEA assessments resulting in Triple Bottom Line (TBL) type sustainability assessments. Note that while they may not be considered sustainability assessment tools as such on their own, EIA and SEA are considered useful tools for sustainability (Hacking and Guthrie, 2006). A comparison and overview of the major differences between EIA, SEA and Sustainability Assessment is presented by Gibson et al. (2001). Pope et al. (2004) introduce "assessment for sustainability", a concept aimed at providing a yes/no answer to the question "is this sustainable?" An overview of the major differences among EIA-led integrated assessment, objective-driven integrated assessment and assessment for sustainability is given by Pope et al. (2004).

2.2.1 TRIPLE BOTTOM LINE (TBL)

The definition of sustainable development from a three-pillar perspective (weak sustainability) was used to underpin TBL (Elkington, 1999), a sustainability accounting method used to account for an organisation's environmental, social and economic impacts. It was initiated in order to incorporate the social pillar which was considered critical for sustainability (Elkington, 2004). Adams et al. (2004, p17) call the triple bottom line "an inspiring metaphor that challenges contemporary corporations". Turning the concept into an accounting tool led to its popularity among companies with Shell being one of the first to adopt and develop tools for accounting (Shell International, 1998). The proliferation of TBL accounting lead to the Global Reporting Initiative (GRI) which developed international standards for reporting (Global Reporting Initiative, 2006; Hussey et al., 2001).

While TBL may have increased awareness of sustainability issues in organizations, it is said to be an inadequate representation for organizational sustainability due to numerous flaws (Buselich, 2002; Norman and MacDonaldl, 2004; Vanclay, 2004; Gray and Milne, 2002; Brown et. al., 2006). According to Buselich (2002), TBL "simply present a list of social, environmental and economic concerns to be analysed in decision-making, rather than integrating and analysing these concerns throughout the assessment process". Gibson (2001, p17) states that TBL can be considered a reductionist approach if the interactions between the three pillars are not understood properly. Furthermore, thinking in terms of pillars rather than systems is also a disadvantage as the concept of pillars neglects the interconnections and interdependencies that are an inherent part of systems such as those involved in sustainability issues.

Critics such as Norman and MacDonald (2004) argue that TBL approach is not novel since the ideas behind a social bottom line were around since Corporate Social Responsibility (CSR). They also argue that a meaningful social bottom line for a firm is philosophically impossible. Others like Vanclay (2004) states that TBL is just a fad and that while it was meant to be heuristic and may have started off as a philosophy, it has become a way of accounting with inadequacies in accounting for social impact (Vanclay, 2004; Gray and Milne, 2002). Yet others such as Lockie and Jennings (2003) note difficulties in developing indicators, notably indicators for the social dimension for which TBL method was first envisioned.

2.2.2 EIA-DRIVEN INTEGRATED ASSESSMENT

EIA-driven integrated assessment is named due its EIA origins as well as the integration of the TBL model's representation of the three pillars (environment, society and economy) (Pope et al., 2004). EIA-driven sustainability assessment is “proponent driven and reactive” (Pope et al., 2005) and assesses a proposal in terms of the three pillars with the purpose of identifying impacts and proposing measures to mitigate negative impacts. The method is based on preventing unacceptable negative impacts in any one pillar by making trade-offs among the three. While the approach can allow for transparency for the economic and social aspects (which are not investigated by EIA), studies indicate that the approach may result in trade-offs which “overtly promote the prevailing economic agenda” (Pope et al., 2004; Jenkins et al., Gibson, 2001; Fuller, 2002) leading to approval of projects that would actually cause environmental degradation.

2.2.3 OBJECTIVES-LED ASSESSMENT

Objectives-led sustainability assessments developed from the belief that ‘sustainability’ is un-measurable or intangible (Fricker, 1998) and concludes that research focus should be on ‘how to measure up to sustainability’ rather than attempting to measure it. Objectives-led assessment is derived from SEA and is based on achieving a particular set of environmental, social and environmental (TBL) objectives and assessing the extent to which the objectives have been achieved (Pope et al., 2004). There are two types of objectives; one is based on aspirational goals, and the other based on thresholds where the objectives can be derived from stakeholder opinion, forecasting (derivation from baseline conditions), backcasting, sustainability principles and tiering (Hacking and Guthrie, 2006).

The objective-led approach is expected to have less trade-offs but would still have some of the same limitations of the original SEA approach. The main concern with the approach is whether addressing TBL objectives would indeed address sustainability. In addition, it is difficult to maintain consistency and compatibility of the objectives for the environmental, economic and social dimensions (George, 2001). When taking into account both the integrated assessments and the objective led assessments, it can be seen that none of the approaches truly capture the essence of sustainability in its true form. Addressing the TBL of environment, social and economic issues are simply not enough to ensure sustainability.

2.2.4 ASSESSMENT FOR SUSTAINABILITY

Most sustainability assessment tools attempt to determine direction, i.e. is the project heading in the correct direction? Assessment for sustainability is based on asking whether a particular project, etc. is sustainable or not (George, 1999; 2001; Sadler, 1999). It aims to determine sustainability by setting sustainability criteria according to societal states. One of the significant requirements for this method is a clear vision or definition of sustainability to provide the sustainability criteria. According to Pope et al. (2004), there are two ways of determining sustainability criteria: TBL factors (bottom-up) and sustainability principles (top-down). Gibson (2001) favours the use of principles-based criteria to avoid TBL associated limitations associated with reductionism as well as the inability to account for interconnections and interdependencies. George (1999) and Sadler (1999) propose the use of principles such as those from Rio Declaration and Agenda 21. While there are many sets of principles that may be used to develop the necessary criteria for assessment for sustainability, the criteria as well as the assessment would be highly dependent upon society’s idea of sustainability which is by no means easy to define.

2.2.5 PRINCIPLE BASED ASSESSMENT

Many researchers prefer the use of sustainability principles to set criteria as they emphasise interconnections and interdependencies between the social, economic and environmental systems and avoids issues such as in integration and trade-offs prevalent in TBL (Sadler, 1999; George, 2001). Sadler (1999) and George (2001) both propose the use of sustainability principles from the Rio Declaration and Agenda 21. Examples of other sets of principles include the Natural Step System's four principles (The Natural Step, 2001) and those developed by the Government of Western Australia for their State Sustainability Strategy (Government of Western Australia, 2003). Example of other principle based assessments are described by Hermans and Knippenberg (2006) where resilience (from Holling's work) and justice (from John Rawls's justice theory) are the two key principles for sustainability; and Kettle (2004; 2006) where a sustainability framework was developed on a hierarchical system of principles and indicators based on the five hierarchical system levels described by Robert (2000).

2.3 EXISTING SUSTAINABILITY ASSESSMENT METHODS AND MODELS

Figure 2 is the framework used to illustrate how the assessments have been classified within this review. This is a modified version of the framework of sustainability assessment tools by Ness et al. (2007). Finnveden and Moberg (2005) have discussed another method of classification (of environmental analysis tools) according to whether they are procedural or analytical where analytical tools may exist within procedural tools. Life Cycle Assessment is an example of an analytical tool while Environmental Management System is mainly a procedural tool.

Rotmans (1998) define integrated assessment as "a structured process of dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders, such that integrated insights are made available to decision makers" (Rotmans, 1998, p. 155). According to Hacking and Guthrie (2008) there is no consensus on what an 'integrated assessments' is. Lee (2002) outlines three definitions of what integrated assessment means:

1. Horizontal integration - sum of different impact categories;
2. Vertical integration – sum of separate assessments; and
3. Incorporating assessments into decision making.

Further categorisation is possible in determining whether they are analytical techniques or are criteria/principle based. Examples of analytical approaches include Life-Cycle Assessment (LCA), Multi-Criteria Analysis (MCA), Cost–Benefit Analysis (CBA), and Risk Assessment (RA) (Hacking and Guthrie, 2008).

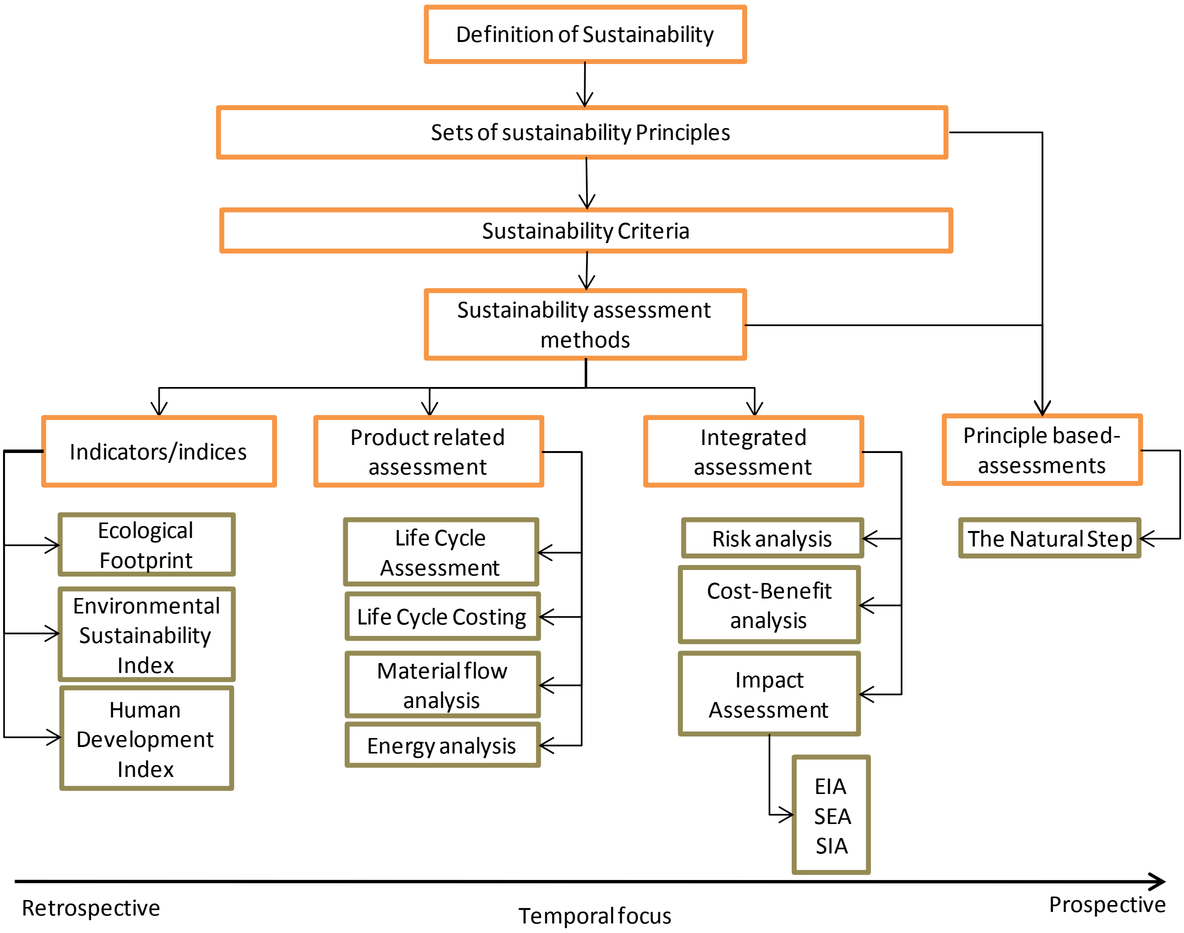

Figure 2: Classification of sustainability assessments

Ness et al. (2007) carried out a review where the assessments are categorised as indicators/indices, product-related assessment, and integrated assessment tools. One of the conclusions of the study is that there is a contradiction in development of sustainability assessment methods where one prefers more specific evaluations (e.g. particular sites) while the other stresses the need for tools that are broader in scope (Ness et. al., 2007). Hacking and Guthrie (2008) presents the results of a literature review of SD tools to identify features that promote them for SD causes. In addition, they have developed a framework that "reconciles the broad range of emerging approaches and tackles the inconsistent use of terminology" (Hacking and Guthrie, 2008, pp73) that is prevalent in the field of sustainability assessment. Paris and Kates (2003) conducted a review of a dozen prominent indicators concluding that there are "no indicator sets that are universally accepted, backed by compelling theory, rigorous data collection and analysis, and influential in policy" due to ambiguity of the definition of sustainability, confusion in terminology, data and methods, etc.

IISD (2005, p6) states that decision makers demand small sets of SD indicators that are linked to policy targets where environmental and social indicators are “compatible with macro-economic indicators and the budgeting process”. Indicators provide useful information on the state of the environment, the economy and society. Furthermore, they also provide information for planning, assessing performance, identifying data gaps, setting priorities and objectives, etc. (Hardi and Barg, 1997).

According to Moffatt et al. (2001), finding theoretically sound indicators that make use of practical and available empirical data have been one of the major problems with sustainability assessment methodologies. Nevertheless, there are now many single-indicator methods as well as methods that aggregate multiple indicators. Rees and Wackernagel (1996) discusses the disadvantage of single-indicator based method concluding that they are misleading since they only account for a single aspect of sustainability. Aggregated indices can assist decision makers by minimising the amount of numerical results they have to go through and therefore lead to increased efficiency (Heycox, 1999; Callens and Tyteca, 1999). However, there are numerous issues concerning subjectivity when methods contain aggregates of multiple indicators (Hueting and Reijinders, 2004). Furthermore, Meadows (1998, p. 4) states that “if too many things are lumped together, their combined message may be indecipherable.”

2.4 SUSTAINABILITY PRINCIPLES

Since there are many definitions for sustainability, researchers have developed various sets of principles that must be met to be considered sustainable. Examples of these can be found in Krotscheck and Narodoslawsky (1996); Holmberg et al. (1996); Diesendorf (1997); Moffatt et al. (2001); Gibson (2002); Boyle and Coates (2005); etc. Sustainability assessment methods are then developed using the principles that are deemed fit for the particular assessment objective. The Natural Step framework for example, was developed using principles by Holmberg et al. (1996). Principles developed by Krotscheck and Narodoslawsky (1996) were used to develop the Sustainable Process Index (SPI). There are also more comprehensive frameworks of principles specifically intended to guide sustainability assessment such as the Bellagio Principles for assessment. Examples of some sets of principles for sustainability follow.

2.4.1 BELLAGIO PRINCIPLES

The Bellagio Principles "serve as guidelines for the whole of the assessment process including the choice and design of indicators, their interpretation and communication of the result" (IISD, 1997). Devuyst et al. (2001: 11) states that the Bellagio principles "are an important basis for any attempt at sustainability assessment". The principles can be used to guide assessments across community, NGOs, businesses, governments, etc. There are 10 categories as follows:

1. Guiding Vision and Goals;
2. Holistic Perspective;
3. Essential Elements;
4. Adequate Scope;
5. Practical Focus;
6. Openness;
7. Effective Communication;
8. Broad Participation;
9. Ongoing Assessment; and
10. Institutional Capacity.

Principle 1 establishes the vision and goals of sustainability; Principles 2 to 5 defines the content of the assessment in terms of what would be included and excluded, etc.; Principles 6 to 8 are process related, particularly in communicating with various stakeholders; and Principles 9 and 10 establishes capacity for continuous assessment (IISD, 1997). The Bellagio Principles have been used in numerous studies including Eawag (2005) for environmental sanitisation, etc.

2.4.2 HANNOVER PRINCIPLES

The Hannover Principles are design based principles by William McDonough Architects (1992) aimed at sustainability of the built environment. These principles were used in the Cradle to Cradle approach (McDonough and Braungart, 2002) and consist of the following:

1. Insist on rights of humanity and nature to co-exist;
2. Recognize interdependence;
3. Respect relationships between spirit and matter;
4. Accept responsibility for the consequences of design;
5. Create safe objects of long-term value;
6. Eliminate the concept of waste;

7. Rely on natural energy flows;
8. Understand the limitations of design; and
9. Seek constant improvement by the sharing of knowledge.

2.4.3 PRECAUTIONARY PRINCIPLE

The 1992 Rio Declaration states the definition or the objective of the Precautionary Principle as “where there are threats of serious irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost effective measures to prevent environmental degradation” (UNCED, 1992). Many, such as Morris (2002), have argued that this definition is contradictory as it demands both action and inaction. The example given to show this contradiction is Rubin’s (2000) asteroid and nuclear capable satellite scenario; the case considers satellites orbiting earth, armed with nuclear weapons so as to prevent the destruction of the planet by shooting the potential asteroid off a collision course. On the other hand however, the weapon’s guidance systems may fail (intentionally or unintentionally) and target earth. Thus the Precautionary Principle has in the past created some controversy as a principle that stifles development. Nevertheless, the principle is incorporated in a number of sets including the World Charter for Nature (UNGA, 1982) and the Governing Council of the United Nations Environmental Programme (UNEP, 1989). Subsequently, the Precautionary Principle has led to a number of multilateral accords including (Hey, 1992; McIntyre and Mosedale, 1997; Cameron and Abouchar, 1991; etc.):

- The UN Framework Convention on Climate Change (1992), article 3(3);
- The Convention on Biological Diversity (1992), preamble; and
- The Bamako Convention on the Ban of Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa (1991), article 4(3)(f).

2.4.4 12 PRINCIPLES OF GREEN ENGINEERING

The 12 principles of green engineering are guidelines for achieving sustainability through science and technology (Anastas and Zimmerman, 2003). The 12 principles according to Anastas and Zimmerman (2003) are summarised below and are aimed at scientists and engineers who design new materials, products, processes and systems:

1. Inherent rather than circumstantial;

2. Prevention rather than treatment;
3. Design for separation;
4. Maximize mass, energy, space, and time efficiency;
5. Output-pulled versus input-pushed;
6. Conserve complexity;
7. Durability rather than immortality;
8. Meet need, minimize excess;
9. Minimize material diversity;
10. Integrate local material and energy flows;
11. Design for commercial afterlife; and
12. Renewable rather than depleting.

McDonough et al. (2003) proposes how the 12 principles may be applied within the Cradle to Cradle framework (McDonough and Braungart, 2002) which is based on the three tenants: 1) Waste equals food; 2) Use current solar income; and 3) Celebrate diversity. While the principles reflect common sense, they are very basic and may not be sufficient for achieving sustainability.

2.4.5 GIBSON'S GENERAL PRINCIPLES

The following is a summary of the Principles developed by Gibson to assist the adoption of sustainability-based decision criteria for environmental assessment in Canada (Gibson, 2001; Gibson et al. 2005).

1. Socio-ecological system integrity;
2. Sufficiency and opportunity;
3. Equity (Intragenerational and Intergenerational);
4. Resource maintenance and efficiency;
5. Democracy and civility;
6. Precaution; and
7. Immediate and long term integration.

Some of the limits of the principles are highlighted by Gibson (2001) and these limits relate to the principles being stated too generally; level of sophistication; and the idea that trade-offs are unavoidable in reality. Rosenthal (2004) for example, states that Gibson's “conception of sustainability is broad and does not provide guidance on specific procedures for conducting a sustainability assessment”. Additionally, ideology such as those pertaining to democracy may not be necessary for sustainability. According to Munslow and Ekoko (1995), "there is no strict correlation between democracy and sustainable development but there are a number of pathologies awaiting the unwary". Good governance rather than a particular political ideology may be beneficial for sustainability.

2.4.6 SUSTAINABILITY PRINCIPLES FOR ENGINEERS

Many including Gibson (2001) understood that traditional engineering thinking would not be sufficient to provide solutions for sustainability. Even with critical thinking, systems perspective, innovation, etc., a clear vision of sustainability is required for practical purposes. Boyle and Coates (2005) developed a set of principles for the Institute of Professional Engineers of New Zealand (IPENZ) to provide guidance for engineering practice for long-term sustainability. The three principles that encompass the key requirements for sustainability are derived from four assumptions correlating to a vision of the future which include: 1. Human existence; 2. Need for food; 3. Need for material and energy; and 4. Unchanged basic human needs. The three principles, the first two of which are closely tied in with elements from the definition of sustainability (WCED, 1987) itself, are:

- Maintaining the viability of the planet;
- Providing for equity within and between generations; and
- Solving problems holistically.

The third principle applied to the first two may take complexity of systems and consequences of human actions into account.

2.4.7 WESTERN AUSTRALIAN SUSTAINABILITY PRINCIPLES

The Western Australia sustainability principles are the result of an exercise conducted by the government of Western Australia to extend the capabilities of environmental impact assessment to involve sustainability criteria (Jenkins et al., 2003). The lack of economic and social criteria for assessment prompted the development of principles summarised here (Government of Western Australia, 2003, p.40.):

1. Long-term economic health;
2. Equity and human rights;
3. Biodiversity and ecological integrity;
4. Settlement efficiency and quality of life;

5. Community, regions, ‘sense of place’ and heritage;
6. Net benefit from development;
7. Common good from planning;
8. Precaution; and
9. Hope, vision, symbolic and iterative change.

2.5 ASSESSMENTS, INDICATORS AND INDICES

Sustainability assessment criteria, also known as indicators and indices are used as yardsticks for measurement against sustainability objectives. There are single indicators (e.g. global warming potential (GWP)) measuring only one aspect of the environment, society or economy; and there are composite/aggregate indicators which integrate sub-indices from any of the three systems. There are many different definitions for sustainability varying according to a particular system or activity. The definitions can influence how sustainability is assessed as criteria for sustainability are derived from definitions. For example, economists define SD as “development that does not decrease the capacity to provide non-declining per capita utility for infinity” Neumayer (2003). As such, there are three types of sustainability theories namely weak sustainability (Hartwick, 1992; Solow, 1993), strong sustainability (Daly, 1996) and a mix of the two (Pearce, 1997). Another example of a theory of sustainability is deep ecology which maintains that humans are an integral part of nature and that the environment and all life encompassed within it has as much right to life (Drengson and Inoue, 1995; Harding, 1997). This theory is primarily based on environmental ethics. Different definitions and interpretations of sustainability can thus lead to many different ways for assessing sustainability.

Composite indicators provide information for policymaking by integrating large masses of information into easily understood formats or indices (Stevens, 2005). However, information in these indices may not be representative of reality and Bossel (1999) outlines how composite indicators may lead to misleading conclusions about sustainability. Further critique of indicators stems from the attempt to reduce complex measurements into simpler, smaller ones (Capra, 2004). Nevertheless, the problem of reductionism is a universal problem in many fields as the complexities of the world, arising from a multitude of interactions, are far too great to account for individually (Bell and Morse, 2008). Table 1 contains short descriptions of some notable methods, indices and tools used for assessing sustainability together with their advantages and disadvantages.

Table 1: Existing sustainability assessment methods and models

Indicator	Type of tool	Description/purpose	Advantages	Disadvantages/ Criticisms	References
			Basic analytical methods		
Emergy	Biophysical model, Analytical	Defined as "the available energy of one kind that has been previously used up, directly and indirectly, to make a service or a product and its unit is the emjoule. Thus is essentially the total amount of energy required to produce a product or carry out a service.	Provides ability to assess relationships between human systems and their environment; incorporates the three systems in its scope.	Ignores human preferences; is based on Maximum Empower Principle; uncertainty issues with Transformity values; and allocation issues.	Odum (1988), Gasparatos et al. (2008), Sciubba and Ulgiati (2005)
Exergy	Biophysical model, Analytical	Defined as "the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state".	Useful for identifying weaknesses in the life cycle; can be useful for policy making; and is science based (fundamental law of thermodynamics).	Fails to identify the causes of the weaknesses; requires a reference state against which analysis is conducted and thus the results are relative to the reference point.	Gasparatos et al. (2008), Dincer (2002).
			Integrated methods		
Triple Bottom Line	Accounting	A sustainability accounting method used to account for an organisation's environmental, social and economic impacts (bottom lines).	Increased awareness of sustainability issues in organizations; used for reporting hence keeps track of progress of each pillar.	Inadequate representation for organizational sustainability; Can be a reductionist approach; does not integrate and analyse concerns throughout the assessment process but rather provides a list of concerns; treats the three pillars as separate entities; implies zero growth in the physical scale of economies and companies.	Elkington, (2004), Adams et al. (2004)
The Natural Step	Principles, objective oriented	A principle based framework that is used for environmental management for strategic decision making.	Increases awareness of issues.	Is argued that the tool is not science-based; ambiguous and complicated; the drivers for unsustainability are not highlighted hence not understood.	Upham, 2000, Chambers et. al, 2000, Sadler, 1999
Sustainability assessment by fuzzy evaluation (SAFE)	Analytical	Is a method for assessing the sustainability of nations resulting in a measure through the use of indicators for environmental integrity, economic efficiency and social welfare.	Data are collectable; easy computation.	Uses specialist software for computation; uses fuzzy logic which require specialist knowledge and understanding of fuzzy logic.	Phillis and Andriantiatsaholinianina, (2001).
Ecosystem Resilience	Theoretical	Is the "magnitude of disturbances that can be absorbed before a system centred on one locally stable equilibrium flips to another".	Direct measure of ecosystem sustainability.	No agreed method for measuring ecosystem resilience.	Arrow et al. (1995)
Barometer of Sustainability	Social and Ecological indicators, Analytical	Evaluates sustainability of the three systems simultaneously while keeping the sustainability of human and ecological systems calculations separate.	Uses a systems approach to assess sustainability; is considered an easy calculation; provides visual results for easy interpretation; treats he human and ecological dimensions equally.	Data availability; the need to determine indicators (and sub-indicators) to use which can be time consuming.	Prescott-Allen (2001); Guijit and Moiseev (2001), Morse (2003), Moffatt et al. (2001).
Ecological Footprint	Biophysical model	Is based on the carrying capacity concept where instead of measuring the number of people that can be supported per given amount of land, it attempts to determine the amount of land (resources) required to support a defined population on an indefinite basis.	Considered to be a good measure of consumption versus resources; The model can be used on many levels ranging from individual to national; takes into account population size and consumption thus indicates demand of society on ecosystems.	Does not take into account environmental issues such as pollution,; does not capture eco-justice elements such as fulfilment of needs and human rights; data availability; can be unsuitable for policy making.	Rees (1992); Rees and Wackernagel (1994); Rees and Wackernagel (1994); Moffat et al. (2001), WWF (2005); EEA (2005b); Global Footprint Network (2005), Gasparatos et al. (2008)

Indicator	Type of tool	Description/purpose	Advantages	Disadvantages/ Criticisms	References
Indicators					
Well-being Index	Social indicator, Analytical	Similar to the barometer of sustainability and is based on the concept that a healthy environment is a requirement for healthy humans.	Is an aggregate of 88 indicators hence sufficient coverage of social issues.	Based on weak sustainability – is focussed on social concerns based on current conditions.	Prescott-Allen, 2001
Sustainability Performance Index	Environmental indicator, Analytical	Is an input oriented indicator that gauges environmental sustainability allowing comparison among nations - calculates the area required for a process to be completely embedded into the biosphere.	Takes a life cycle approach.	Data availability, focus mainly on the environmental systems.	Narodoslawsky and Krotscheck (2004), Lundin (2003).
Living Planet Index	Ecological Indicator, Analytical	Measure of the state of natural ecosystems according to the abundance of animal species they support.	Useful time-series indicator since ecosystem health can be linked to species population trends.	Availability and representativeness of data.	WWF (2002).
Product Sustainability Index	Product, Analytical	Is based on exergy calculations hence is “the fraction of the area per inhabitant related to the delivery of a certain product or service unit”. The PSI consists of aggregate of environmental, social and economic indicators.	Useful for identifying weaknesses in the life cycle; can be useful for policy making.	Fails to identify the causes of the weaknesses; requires a reference state against which analysis is conducted and thus the results are relative to the reference point.	Krotscheck and Narodoslawsky (1996)
Environmental Sustainability Index	Indicator, criteria based, Analytical	Integrated tool that serves to identify key issues in society and national level environmental programs.	Helps rank governments internationally with respect to leadership in selected issues.	Data availability, too many indicators leading to uneven spread over core issues.	WEF (2005)
Genuine Progress Indicator	Economic + Social indicator, Analytical	An adjusted Gross Domestic Product (GDP) which now reflects the well-being of the people - aimed at reflecting the state of the economy more accurately.	Takes into account economic contributions from household and volunteer work; social aspects such as crime and pollution, is considered a useful tool for policymaking.	Is based on current flows thus does not take into account stocks or future capacity.	Moffatt et al. 2001, Daly and Cobb (1990), Lawn (2003).
Genuine Savings Indicator	Economic + Social indicator, Analytical	Is essentially an accounting framework which includes welfare measures that account for resources, their discovery as well as environmental impacts where negative savings indicate unsustainability.	Values are monetised which enables simple aggregation.	Is based on weak sustainability; fails to account for intra-generational equity.	Hamilton et al. (2003), World Bank (1995), Peace and Atkinson (1993), Moffatt et al. (2001)
Human Development Index	Social indicator, Analytical	A social indicator based on life expectancy, adult literacy together with years of education (primary, secondary and tertiary enrolment) and GDP per capita expressed in monetary terms.	Capacity to represent social or human dimensions.	Methodological issues, inability to account for differences in human development within countries, comparing results over time is difficult due to the continuous evolution of the methodology.	United Nations (1990), Booysen (2002), Sagar and Najam (1998), McGillivray (1991).
Sustainable Process Index	Principle based, Analytical	Compares human mass and energy flows with natural flows and thus measures the measures the ecological impact of a process.	Takes a life cycle perspective; evaluation is compatible for technologies, products and regions; Sensitive to technology changes; Different impacts can be compared directly.	Data availability in terms of mass flows; does not consider social and economic concerns.	Krotscheck and Narodoslawsky (1996)
Carbon Footprint	Environmental indicator	The total set of greenhouse gases (GHG) emissions caused by an organization, event or product.	Able to assess organisation and product footprint, focuses on greenhouse gas reduction which is a significant current issue.	Only focuses on carbon accounting and neglects other significant issues.	Carbon Trust (2010)
Dow Jones Sustainability Index	Economical, Analytical	Is used to identify and track the performance of sustainably run companies.	Shows which companies are considering issues relevant to sustainability; is a benchmarking tool.	Not an assessment tool for sustainability.	Cerin and Dobers (2001)

Indicator	Type of tool	Description/purpose	Advantages	Disadvantages/ Criticisms	References
		Tools for sustainability			
Life Cycle Assessment	Environmental, Analytical	Analytical tool to determine environmental impact of products and services along their life cycles.	Standardised framework; easy to understand and considers life cycles hence can obtain data on all stages of a product to be assessed.	Complicated computation; lack of credibility as an impartial tool; does not address localised impacts; LCA is generally a steady state approach rather than a dynamic one; is based on linear modelling which limits a true understanding of complex environmental issues.	Udo de Haes (1993), ISO (2006), Guinée et al. (2001)
Life Cycle Costing	Economic, Analytical	Is an economic analytical tool used to determine "total costs of a product, process or activity discounted over its lifetime".	Variations of the method can account for hidden costs such as the benefits of pollution control.	Quantification of costs, especially future costs related to damages where monetising of certain damages are considered unethical.	Gluch and Baumann (2004), Shapiro (2001), White el al., (1996)
Social Life Cycle Assessment	Social, Analytical	Tool to determine social impact of products and services along their life cycles.	Can give local social impacts depending on the method used.	Methods still in their infancy; local data rather than homogenised data regarding the social impacts are required.	Hunkeler (2006), Dreyer et al. (2006), O'Brian et al. (1996).
Risk Analysis	Procedural, Analytical	"Risk assessment is the process of estimating the likelihood and magnitude of the occurrence of an unwanted, adverse effect".	May be 'a measure of unsustainability', understanding of potential hazards may provide means of avoiding or mitigating.	Validation of probabilities can be problematic; suffers from the need for extensive data and is also difficult to communicate.	Tweeddale and Mehra (1995), Grey and Wiedemann (1997), Skelton (1996), Fairbrother and Turnley (2005)
Critical Limits and Critical Natural Capital	Principle based, analytical	A sustainability assessment approach based on Ecological Economics.	Attempts to takes into consideration critical biophysical limits.	Difficult to determine quantitative thresholds (i.e. the critical limits) based on current knowledge.	Costanza and Daly (1987), Pearce (1987), Ekins and Simon (2003), Ekins et al. (2003)
Cost Benefit Analysis	Economic, Analytical	Appraises projects or proposals in terms of costs and benefits over time to evaluate cost effectiveness.	Easy to communicate, wide range of application.	Considered to be over-simplistic and is subjective as it depends on decision maker's priorities.	Wrisberg and Udo de Haes (2002)
Multi-Criteria analysis	Procedural	A tool that considers economic, environmental and social issues, examining the performance of a system based on those criteria to prioritise issues.	Allows stakeholder input; can be both qualitative and quantitative.	Does not give definitive solutions to problems as the result consist of trade-offs among objectives – one area improves while another deteriorates.	Wrisberg and Udo de Haes (2002)

2.5.1 THE NATURAL STEP (TNS)

TNS is a principle based framework that is used for environmental management for strategic decision making (Upham, 2000). It was conceived due to the view that excessive scientific concern for environmental assessment was in fact hindering sustainability. The fundamental principles underlying the TNS framework are deeply rooted to the limits to growth concept, and assume that the limits to growth have already been exceeded at a global scale. TNS consists of four system criteria for sustainability (Sadler, 1999, p22):

1. Substances from the earth's crust must not systematically decrease in nature;
2. Substances produced by society must not systematically increase in nature;
3. The productivity and diversity of nature must not be systematically deteriorated; and
4. Basic human needs must be met everywhere.

According to Upham (2000), TNS "implies zero growth in the physical scale of economies and companies, without stating this explicitly." Upham (2000) also states that:

> "TNS is rhetorical in its use of risk assessment, emphasising a rise-in-concentration criterion for the sake of consensual argument, in the knowledge that it is inadequate for environmental protection. TNS has profound and valuable implications for contemporary economies, but users should be aware that TNS is primarily designed as a persuasive argument, and is not wholly science based."

Upham (2000) provides further discussion on the advantages and disadvantages of TNS framework for sustainability. TNS is a relatively simple approach based on systems thinking that works to link ideas and policies. However, the lack of understanding with respect to the causes of unsustainability and ambiguity with respect to its use of Laws of Thermodynamics, or as a "loose metaphor" (Hammond, 2004) is a hindrance (Chambers et. al, 2000).

2.5.2 CRITICAL LIMITS AND CRITICAL NATURAL CAPITAL (CNC)

Critical Limits is a sustainability assessment approach based on ecological economics where studies have been conducted by researchers such as Costanza and Daly (1987), Pearce (1987), Ekins and Simon (2003), Ekins et al. (2003), etc. The project CRITINC, funded by the European Commission, involved identifying CNC (CNC enables the maintenance of significant environmental functions) and developing a framework to apply the strong sustainability principle (Ekins, 2000). The project was largely based on the maintenance of natural capital, which is an inherent requirement for environmental sustainability (Ekins, 2003). It is based on three specific criteria:

1. Maintenance of human health;
2. Avoidance of threat; and
3. Economic sustainability.

These criteria are used to derive seven principles, five of which deal with environmental considerations. The sixth is based on the Precautionary Principle and the seventh considers aesthetic and cultural considerations as social concerns (Ekins, 2000). One of the main issues with CNC is that it is difficult to determine quantitative thresholds (i.e. the critical limits) based on current knowledge. However, the framework was tested in the United Kingdom, France, Germany, Italy, Netherlands and Sweden where river systems, agricultural land, forests, air quality, coastal wetlands and urban ecosystem functions were assessed respectively.

2.5.3 FOOTPRINTS: ECOLOGICAL, CARBON AND WATER

The Ecological Footprint (EF) is based on the carrying capacity concept where instead of measuring the number of people that can be supported per given amount of land, it attempts to determine the amount of land (resources) required to support a defined population on an indefinite basis (Rees, 1992; Rees and Wackernagel, 1994; Rees and Wackernagel, 1994; WWF, 2005; EEA, 2005b; Global Footprint Network 2005). While EF is a good measure of consumption versus resources, the method does not take into account many factors that cannot be measured on a land basis. For example, environmental issues such as pollution cannot be accounted for using land as a measure. Another potential issue concerns how fossil fuels and metals are accounted for by the EF framework. The possibility of fossil fuel depletion is not accounted for directly, but instead, it accounts for "waste disposal demands needed to absorb CO_2 emissions from burning fossil fuel" (Senbel et al. 2003). Similarly, with metals and minerals, the limiting factor is considered to be extraction of the resource rather than the finite nature of the resource (Wackernagel and Rees, 1996).

The model can be used on many levels ranging from individual to national. The method relies on normalisation with implicit weightings where statistical data on national consumption is used (Wackernagel and Rees, 1997). There are also some issues with data availability hence overall EF can be used to raise awareness but has limited use to policy makers (Moffat et al., 2001). EF has been applied to cities (Wackernagel, 1998) and has also been extended to use in businesses (Chambers and Lewis, 2001; Holland, 2003). Some of the limitations of applying to business include the inconsistent ways with which risks and uncertainties are dealt; the lack of distinction between the types of environmental capital (non-renewable or renewable); the inability to capture eco-justice elements such as fulfilment of needs and human rights; inability to account resource depletion in terms of bio-productive land; as the inability to account for pollution or other environmental impacts that are not transferable to land impacts; etc. (Holmberg et. al, 1999; Gasperatos et al, 2008). Other footprints such as the carbon footprint and water footprint may complement the ecological footprint though they are focussed on greenhouse gas emission and water use respectively.

Carbon footprint is defined as “the total greenhouse gas (GHG) emissions caused directly and indirectly by an individual, organisation, event or product, and is expressed as a carbon dioxide equivalent (CO_2e)” (Carbon Trust, 2010). The method takes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) into account when calculating the footprint. Thus far, two types of footprints, organisational footprint and product footprint, can be calculated. The result is a measure of carbon contribution towards global warming and climate change and is expected to be of many uses ranging from internal use to reduce the footprint and subsequently reduce costs such as cost of power; certification of product, advertising for enhanced brand reputation, engaging supply chain, etc. The carbon footprint is specifically for carbon accounting and hence does not account for other significant issues related to sustainability.

Water footprint is defined as “the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business” (Hoekstra et al., 2009) and was introduced by Hoekstra and Hung (2002) for the purpose of linking consumption patterns and impacts on water. The water footprint takes direct and indirect uses of freshwater into account by investigating the supply chain, accounting for water consumption by source as well as pollution by type. It takes into account blue water resources (i.e. surface and ground water); green water (rainwater stored as soil moisture); grey water (with respect to pollution, defined as “the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards” (Hoekstra et al., 2009)) and thus the water footprint goes beyond a measure of water withdrawal. The method has four steps:

1. Setting goals and scope ;

2. Water footprint accounting;
3. Water footprint sustainability assessment; and
4. Formulation of response.

The water footprint is aimed at revealing water use, including hidden water use, so as to quantify water resource use (Hoekstra and Chapagain, 2008). One advantage of water footprint is that it can be explicit in terms of the spatial and temporal impacts. However, there are discrepancies in impact associated with the need for auxiliary information. One example to illustrate this is the impact of growing crops in regions where water is scarce as opposed to regions where water is abundant. The regions would have different water impacts even though the water requirement for growing the crop is equivalent. Furthermore, the current water footprint method has issues with ill-defined system boundaries and inventory analysis where equal weighting is given to blue, green and grey water which may not be scientifically sound (Oki, 2010).

2.5.4 EMERGY

Coined by Scienceman (1987) and Odum (1988), emergy is defined as "the available energy of one kind that has been previously used up, directly and indirectly, to make a service or a product and its unit is the emjoule (ej)". While emergy is able to use any energy unit, it uses solar emjoule (sej) as the base unit. Note that emergy is not equivalent to embodied energy which is defined as "the total (direct and indirect) energy required for the production of economic or environmental gods and services" (Costanza, 1980). While both emergy and embodied energy account for energy, they are quite distinct (Brown and Herendeen, 1996). One of the most significant differences is that embodied energy analysis does not include environmental energies (solar, geophysical, tidal, etc.), relying only on heat energy of fuels (Brown and Herendeen, 1996; Cleveland, 1992).

Sciubba and Ulgiati (2005) state that emergy is a measure of sustainability because of its ability to assess relationships between human systems and their environment. Emergy is calculated in four stages: 1. Emergy diagrams; 2. Emergy evaluation tables; 3. Energy indices; and 4. Communication of result. The calculation consists of three aggregated emergy flows: renewable resources; non-renewable production; and imports or exports (Giannetti et al., 2006). While emergy incorporates the three systems (environmental, social and economic) in its scope, some of the criticisms according to a review by Gasparatos et al. (2008) include that it ignores human preferences, is based on maximum empower principle (Odum, 1996) and has issues with transformity values.

2.5.5 EXERGY

Exergy, or energy available, is based on a universally accepted methodology based on improving efficiency of thermal process. It can be defined as "the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state" (Gasparatos et al., 2008). The technique allows for precise measurements due to its origins based on the laws of thermodynamics. Kotas (1985) and Szargut et al. (1988) describe the methodology used to calculate exergy. The method is useful for identifying weaknesses in the life cycle much like in LCA but it fails to identify the causes of the weaknesses. The method requires a reference state against which analysis is conducted and thus the results are relative to the reference point. Impact of energy utilisation on the environment can be measured thus it can be useful for policy making (Dincer, 2002). Work by researchers such as Hammond (2004), Bastianoni et al. (2005), Ulgiati et al. (2006), etc note the significance of exergy as a tool for sustainability.

2.5.6 BAROMETER FOR SUSTAINABILITY

This method was developed by the International Union for the Conservation of Nature and Natural Resources (IUCN) in the 1990s. It maintains that sustainability is an aggregate of two sub-systems: the ecosystem and human system, thus attempts to measure sustainability by determining the sustainability of the sub-systems separately (Prescott-Allen, 2001; Guijit and Moiseev, 2001). There are no tradeoffs thus if one of the systems is not sustainable, then the entire system cannot be sustainable. While the method allows for easy calculation as well as graphical presentation of results, it is said to be time consuming and lacking in data for more complex assessments (Bossel, 1999; Prescott-Allen, 2001)

2.5.7 ENVIRONMENTAL SUSTAINABILITY INDEX (ESI)

ESI by the World Economic Forum is an integrated tool that serves to identify key issues in society and national level environmental programs. It is derived from 68 indicators for 148 countries and is aggregated as follows:

1. Environmental systems consisting of sub-indices for air quality, water quantity, water quality, biodiversity, and land;
2. Reducing environmental stresses consisting of sub-indices for air pollution, water stresses, ecosystem stresses, waste and consumption pressures, and population growth;
3. Reducing human vulnerability consisting of basic human sustenance and environmental health;
4. Social and institutional capacity consisting of science and technology, freedom to debate, environmental governance, private sector responsiveness, and eco-efficiency; and
5. Global stewardship including participation in international collaborative efforts to reduce greenhouse gas emissions and transboundary environmental pressures.

It also helps rank governments internationally with respect to leadership in selected issues (WEF 2005).

2.5.8 WELL-BEING ASSESSMENT (WI)

The WI by the World Conservation Union (IUCN) is an aggregate of 88 indicators for 180 countries (Prescott-Allen, 2001). WI is similar to the Barometer of sustainability because it too is based on the concept that a healthy environment is a requirement for healthy humans (Prescott-Allen, 2001). WI is thus the mean of Human Well-being Index (HWI) (consisting of Health and population, Welfare, Knowledge, Culture and Society, and Equity sub-indices) and Ecosystem Well-being Index (EWI) (consisting of land, air, water, species and genes, and resource use). HWI is based on 31 indicators while EWI are based on 51 indicators. The results for this study has shown that the most sustainable countries are those in northern Europe (Sweden, Finland, Norway, and Iceland) while the least are Afghanistan and Iraq (Paris and Kates, 2003).

2.5.9 GENUINE SAVINGS INDICATOR

The GS index, also known as Adjusted Net Savings, by Peace and Atkinson (1993) for The World Bank, is based on weak sustainability. The index is essentially an accounting framework which includes welfare measures that account for resources, their discovery as well as environmental impacts (Hamilton et al. (2003)) where negative savings indicate unsustainability (World Bank, 1995).

> Genuine Savings = Gross national savings + educational expenditure – consumption of fixed capital – depletion of natural resources – pollution (World Bank, 2002).

The values are monetised which enables simple aggregation (Hamilton et al. 1997; Pearce 2000). While the calculations incorporate fundamental components for sustainability assessment, it fails to account for intra-generational equity (Moffatt et al., 2001).

2.5.10 SUSTAINABILITY PERFORMANCE INDEX (SPI)

SPI was developed to gauge environmental sustainability allowing comparison among nations. According to Narodoslawsky and Krotscheck (2004), the core of SPI is the calculation of the area required for a process to be completely embedded into the biosphere including area required for life cycle components such as raw material extraction and refining, energy, infrastructure, staff, storage, etc. (Lundin, 2003). Thus SPI is an input oriented indicator. Work carried out by the developers of SPI (Yale University) extended towards developing the Environmental Performance index (EPI) which is an out-come oriented indicator measuring environmental health and ecosystem vitality for use in policymaking.

2.5.11 LIVING PLANET INDEX

The living planet index (LPI) was developed by the World Wildlife Fund (WWF) to track population trends of different species and is defined as a measure of the state of natural ecosystems according to the abundance of animal species they support (WWF, 2002). It measures over 1100 species of vertebrates in terrestrial, freshwater and seawater ecosystems. The restriction of the index to vertebrates is due to data availability where data for vertebrates exist from the 1970s. The LPI is a useful time-series indicator since ecosystem health can be linked to species population trends. However the index is limited due to availability and representativeness of data (Loh et al, 2005). It is currently being used to test progress towards the 2010 goals from the Convention on Biological Diversity (CBD), a treaty adopted by 188 countries in Rio de Janeiro in June 1992.

2.5.12 GENUINE PROGRESS INDICATOR

The GPI consists of an adjusted Gross Domestic Product (GDP) which now reflects the well-being of the people. The GPI evolved from the Index of Sustainable Economic Welfare (ISEW) developed by Daly and Cobb (1990) via work by Cobb, Halstead and Rowe (1995).
"ISEW = consumer expenditure adjusted to account for income distribution + non-defensive public expenditures + growth in capital and net change in international position + estimate of non-monetarised contributions to welfare – defensive private expenditure – cost of environmental degradation – depreciation of natural capital" (Moffatt et al. 2001; 137)

The ISEW was developed due to limitations of the GDP which is a commonly used national measure of income (Lawn, 2003). The main limitation of the GDP includes its inability to distinguish between activities that lead to improvements or damage. The aim of GPI is similar to that of ISEW which was aimed at reflecting the state of the economy more accurately. The only difference between the ISEW and the GPI according to Moffatt et al. (2001) include the exclusion of public and private defensive expenditure and inclusion of deductions for loss of leisure time, under employment and loss of forest. A rising GPI denotes increasing economic sustainability. The GPI takes into account economic contributions from household and volunteer work, social aspects such as crime and pollution. Moreover, it takes into account depreciation of natural capital. The GPI is considered a useful tool for policymaking but it is based on current flows thus does not take into account stocks or future capacity (Moffatt et al., 2001; Neumayer, 2000).

2.3.13 HUMAN DEVELOPMENT INDEX (HDI)

HDI is a social indicator based on life expectancy, adult literacy together with years of education (primary, secondary and tertiary enrolment) and GDP per capita expressed in monetary terms (United Nations, 1990). There is an abundance of criticism of the HDI ranging from methodological (Booysen, 2002), data related (Murray, 1991) and its inability to account for differences in human development within countries (Sagar and Najam, 1998). The methodological and data related issues are applicable to many methods. The advantage of HDI is its simple calculation as well as its ready use by policymakers (Moffatt et al., 2001). However, Morse (2003) notes that due to the evolution of the methodology since 1990, comparing results over time is difficult.

2.5.14 PRODUCT SUSTAINABILITY INDEX

PSI, developed by Ford of Europe, is a tool that can be used to assess products or services by engineers. It is “the fraction of the area per inhabitant related to the delivery of a certain product or service unit” (Krotscheck and Narodoslawsky, 1996). The methodology is based on exergy calculations hence have equivalent advantages and disadvantages as exergy as a tool for sustainability assessment (Krotscheck and Narodoslawsky, 1996). The PSI consists of aggregate of environmental, social and economic indicators: Life Cycle Global; Warming Potential; Life Cycle Air Quality Potential; Sustainable Materials; Restricted Substances; Drive-by-Exterior Noise; Mobility Capability, Safety; Life Cycle Cost of Ownership.

2.5.15 SUSTAINABILITY ASSESSMENT BY FUZZY EVALUATION (SAFE)

The SAFE model was aimed at assessing sustainability of nations and results in a measure through the use of indicators for environmental integrity, economic efficiency and social welfare (Phillis and Andriantiatsaholinianina, 2001). It consists of two main (primary) indicators: ecological sustainability (ECOS) and human sustainability (HUMS). ECOS consists of four sub-indices (secondary) for water quality; land integrity; air quality; and biodiversity. HUMS also consist of four sub-indices: political aspects; economic welfare; health; and education. Each sub-index consists of three (tertiary) indicators: pressure; state; and response. Each of these sub-sub-indicators has a function for basic indicators where computation is initiated (Kouloumpis et al., 2008; Phillis and Kouikoglou, 2009). The advantage of this model is based on computation, use of specialised software and understanding of fuzzy logic. According to Andriantiatsaholiniaina et al. (2004), “fuzzy logic is capable of representing uncertain data, emulating skilled humans, and handling vague situations where traditional mathematics is ineffective.”

Fuzzy set theory is used in the methodology for its ability to handle multi-valued logic (Zimmerman, 1996) which is able to identify the degree to which an event occurs rather than whether an event occurs. This means that it can assess intermediate possibilities between sustainability and unsustainability (Kosko, 1992). The main steps undertaken by the method as given in Figure 3 are:

1. Transform real values into linguistic values by fuzzification;
2. Apply fuzzy reasoning in the form of "IF-THEN", "AND", "OR" linguistic rules (express interdependencies among sustainability factors) according to linguistic variables. Linguistic variables are operated via membership functions, a fundamental component of fuzzy models that define soft thresholds enabling practical assessment; and
3. Transform back to real values via defuzzification.

While the method attempts to take a systems perspective, it remains to be reductionist via the use of separate indicators. Fuzzy logic would reveal some interconnections between systems but the method depends on the models used for fuzzification and defuzzification. Furthermore, fuzzy set theory results in a mathematical framework that links "human expectations about SD, expressed in linguistic propositions, to numerical data, expressed in measurements of SI" (Cornelissen, 2003). This invariably requires the input of experts who define the human expectations and thus the method can be subjective.

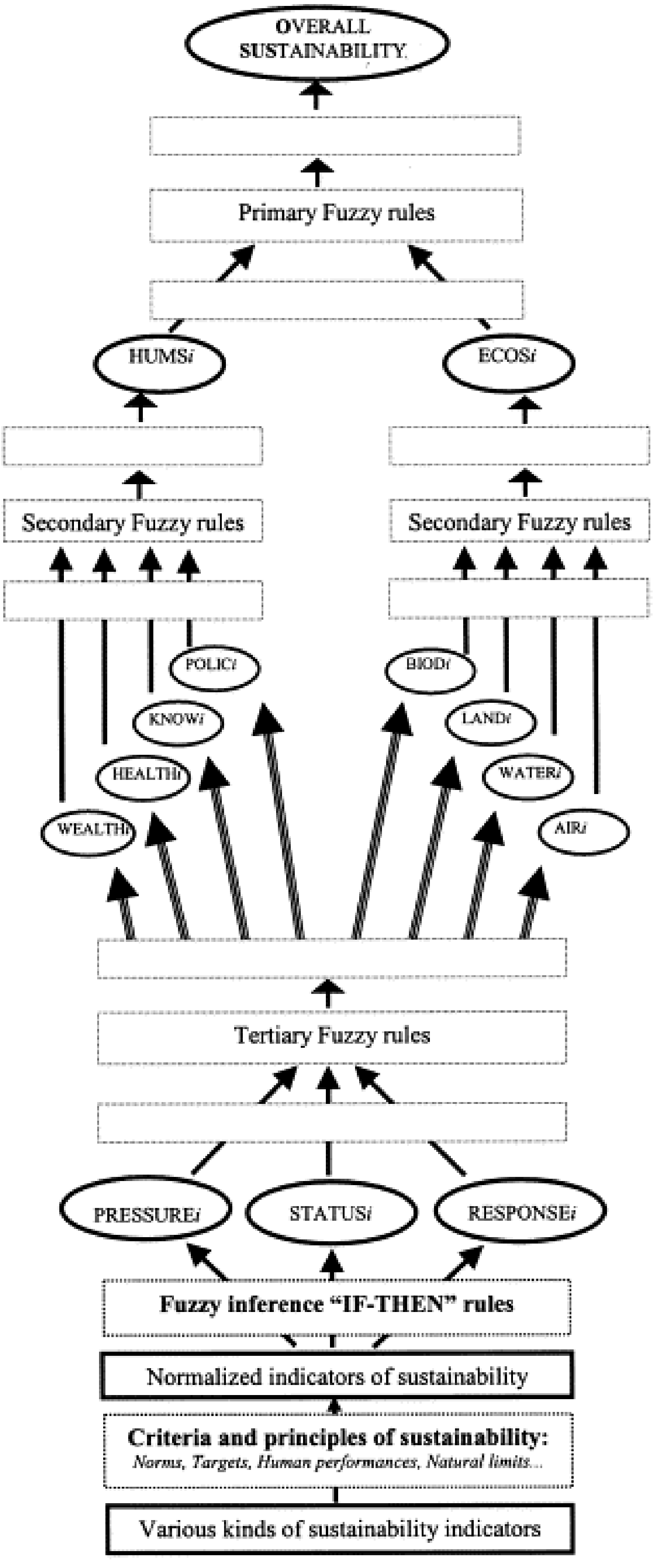

Figure 3: SAFE methodology (Reproduced from Phillis and Andriantiatsaholinianina, 2001)

2.5.16 LIFE CYCLE ASSESSMENT (LCA)

LCA is a tool that has been used extensively to determine environmental impact of products and services along their life cycles (Ness et al., 2007). The method is based on a framework which has been standardised via the establishment of guidelines and principles by the International Standards Organisation (ISO, 2006; Guinée et al., 2001). The LCA framework is given in Figure 4.

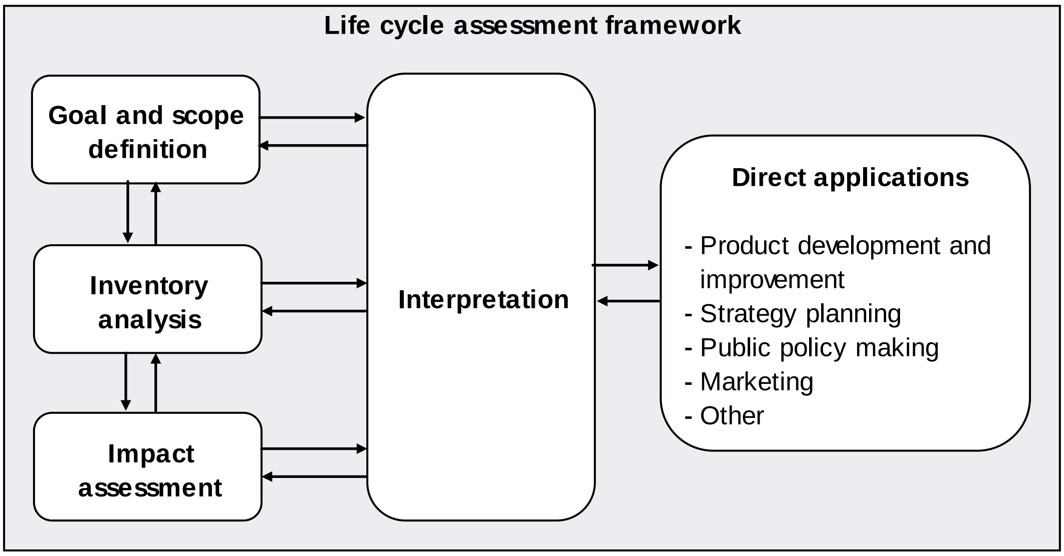

Figure 4: Phases of Life Cycle Assessment (Reproduced from ISO, 1997)

LCA use can be categorised as industrial and governmental. Some of the industrial uses of LCA include:

- Strategic planning (White, 1992), environmental strategy development (Christiansen et al, 1995) or formulation of company policy (UNEP, 1996);
- Product and process design (Rydberg, 1994), improvement and optimisation where:
    - Alternative materials, products, processes, or activities within the organisation are compared;
    - Resource use and release inventory information from other manufacturers are compared; and
    - Personnel responsible for reducing the environmental burdens associated with products, processes, and activities such as designers and engineers are trained;
- Identification of environmental improvements opportunities and tracking improvement progress;
- Product information as well as to provide the baseline information necessary for carrying out other LCA studies;

- Marketing or support for specific environmental claims;
- Support of the establishment of purchasing procedures or specifications; and
- Environmental auditing and waste minimization.

Some of the governmental uses of LCA include:

- Labelling or product declaration (Clift, 1993; Goedkoop and Spriensma), including setting criteria for eco-labelling (Fet and Skaar, 2006);
- Public education (Baumann, 1998) and communication to help the public understand resource use and release characteristics associated with products, processes, and activities;
- Policy-making; and
- Support of the establishment of purchasing procedures or specifications.

(SETAC, 1991; SETAC, 1993)

While LCA use has been extensive since its conception, there have been a number of issues with the method:

- The most significant communication problem related to LCA includes its lack of credibility as an impartial tool (Udo de Haes, 1993);
- LCA is a supporting or analytical tool and according to Udo de Haes (1993), "it can never replace decision making". Thus its direct uses, while allowing for greater insight to the respective industry, are somewhat limited;
- While it is unlikely LCA can be misused to discriminate against competitor product. One such case was the introduction of policy to heighten advantages of refillable/reusable packaging by the governments of Denmark and Germany (EUROPEN, 2001). It is argued that the measure created trade barriers affecting competition and hence has the potential to impair innovation. This case highlighted the need for consideration of environmental, economic and social dimensions as a complete package rather than just relying on environmental data;
- LCA does not provide a framework for the consideration of local risk assessment hence does not address localised impacts. This is also the case of temporal issues where LCA is generally a steady state approach rather than a dynamic one (Guinée et al., 2001);
- LCA does not take market mechanism or technical developments and the effects on these developments into account. This is due to its focus on physical features of industrial activities;

- LCA is based on linear modelling which limits a true understanding of complex environmental issues; and
- LCA is primarily a comparative tool; it does not provide mechanisms for path breaking, focusing only on stepwise improvement.

Further work including reviews of the significance and critiques of LCA can be found in Ayres (1995); Ehrenfeld (1997); Frankl and Rubik (2000); Ciroth and Becker (2006); Reap et al. (2008a, 2008b); Finnveden et al. (2009), etc. Current research ranges from the adaptation of the LCA technique for assessing various products and services to integration of principles and other methods to assess beyond the environmental impacts (such as incorporation of social factors (Dreyer et al., 2006) and economic factors (Norris, 2001; Rebitzer and Hunkeler, 2004)). Others such as Andersson et al. (1998) have discussed the incorporation of sustainability principles in the LCA methodology itself, using the four socio-ecological principles developed by Holmberg et al (1992). Their methodology was to incorporate the principles at each stage of the LCA (goal and scope, inventory analysis, impact assessment and interpretation).

2.5.17 LIFE CYCLE COSTING

Life Cycle Costing (LCC), also known as Total Cost Assessment (TCA) and Full Cost Accounting (FCA) (Hunkeler and Rebitzer, 2002), is an economic analytical tool used to determine "total costs of a product, process or activity discounted over its lifetime" (Gluch and Baumann, 2004). Traditionally, LCC was used to compare investment costs to determine the best approach and does not take into account hidden costs such as those concerning the environment (Shapiro, 2001). However, LCC has been identified as a tool to evaluate the economic dimension of sustainability (Klöpffer, 2003) hence has been integrated into life cycle management (Norris, 2001).

There are many methods for LCC, however, Gluch and Baumann (2004) identify Life Cycle Cost Assessment (LCCA) and Full Cost Environmental Accounting (FCEA) as two LCC methods that incorporate environmental costs in the assessment. Social costs can also be included in LCC as described by White et al. (1996). According to White et al. (1996), TCA accounts for hidden costs such as the benefits of pollution control. Additionally, according to Shapiro (2001), external costs from environmental damage from the product can also be included into LCC as costs to society rather than costs to the company. Some of the issues with LCC concerns quantification of costs, especially future costs related to damages where monetising of certain damages are considered unethical (Klöpffer, 2003).

2.5.18 SOCIAL LIFE CYCLE ASSESSMENT

Of the three dimensions, the life cycle assessment concerning the social dimension has been the least developed and hence methods are still in their infancy. One of the earliest works on SLCA is the methodology for Social and Environmental Life Cycle Assessment (SELCA) developed by O'Brian et al. (1996). Dreyer et al. (2006) developed a Social Life Cycle Impact Method (LCIA) to help facilitate social responsibility by companies (determine social impacts from suppliers and the company). They note that social LCA is about impacts to people hence social impacts during the life cycle of the product must be determined. They also maintain that there is no need to consider the process stage since health impacts are already considered as part of environmental LCA.

Another methodology, described by Hunkeler (2006), is a mid-point based method with goals compatible to that of both LCC and LCA. This method utilises labour hours as an intermediate for calculation, arguing that realistically, the gap between the rich and poor causes societal issues and hence there are implicit links between employment, wealth and social well-being. The method differs from LCC and LCA in a number of ways. For example, while LCA homogenises local impacts to average global impacts, SLCA tries to determine the social impacts (e.g. employment) at a local level. This would mean that local data, rather than homogenised data regarding the social impacts are required. Hunkeler (2006) goes onto categorising this method as a micro-economic assessment because it "examines the effect of product substitution on the state of average workers in countries where the product life cycle has an effect". The difference between macro-economic social assessment and micro-economic societal assessment is that effects of government programs are covered explicitly for macro-economic assessments (Hunkeler, 2006).

2.5.19 INTEGRATED LIFE CYCLE ASSESSMENTS

Klöpffer (2003) states that "only life cycle based methods have the potential for sustainability assessments". As mentioned above, each of the tools (LCA, LCC and SLCA) separately can be considered as tools that assess the environmental, economic and social dimensions of sustainability. Numerous works have integrated LCA and LCC successfully (Norris, 2001; Rebitzer, 2002). In the context of sustainability, Rebitzer and Hunkeler (2003) define a combined LCC, LCA together with social component as:

> "An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (supplier, producer, user/consumer, end-of-life actor), with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future."

Klöpffer (2003) notes that a combination of the integrated LCC and LCA methodology by Rebitzer (2002), and the SLCA methodology by O'Brian et al. (1996) would lead to a complete sustainability assessment tool. The possibility of double accounting when using the three methods is noted as an issue for integration (Klöpffer, 2003), however, defining clear scope and boundaries can minimise double accounting. More work with SLCA is required for an integrated assessment to be successful. Another example is the integration of Ecological Footprint with elements from LCA and The Natural Step in order to improve the Ecological Footprint as a tool for assessing sustainability (Anderle, 2002).

2.5.20 RISK ASSESSMENT (RA)

Risk is unique in that every human venture, be it an individual crossing the road or governments implementing global initiatives, undergoes some sort of formal or informal RA. One of the earliest definitions of RA is "the combination of the sum of the probabilities of risk events and their consequences" (Burton and Pushchak, 1984). The fundamental steps of RA listed by Smith (2004) are given as: 1. Description of a threat or hazard; 2. The extent of exposure to the hazard; 3. Estimation of a risk; and 4. Consideration of uncertainties in the estimation. Today, a number of frameworks for risk assessment and management exist to aid in the process. The steps in risk management according to the Australian/ New Zealand risk management standard 4360: 2004 are given in the framework in Figure 5.

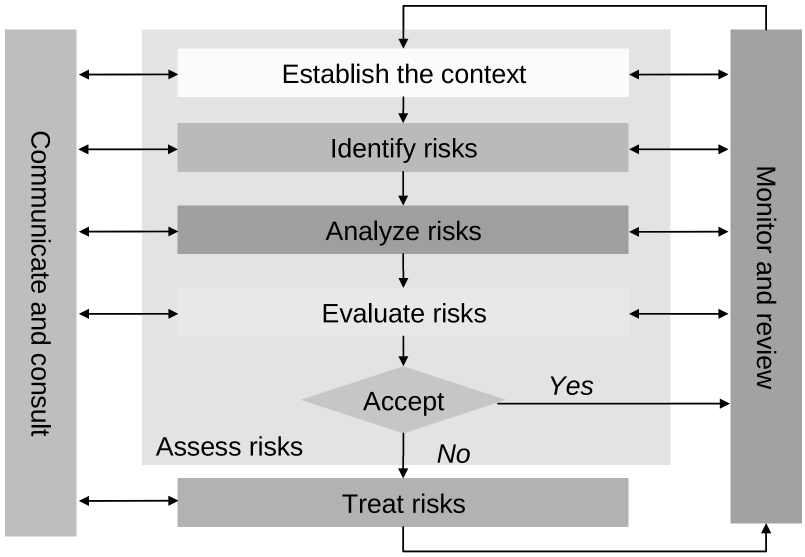

Figure 5: Risk Management framework (AS/NZS4360: 2004)

Many researchers have suggested the use of risk as a tool for sustainability (Blockley and Heslop, 2001; Reinert et al, 2006). A number of studies that use risk as a cornerstone for assessing sustainability exist. For example, Chesson et al. (1999) discuss the framework developed for a bureau within the Department of Agriculture, Fisheries, and Forestry in Australia. The framework is an example of a problem-oriented approach based on the definition of Ecologically Sustainable Development (ESD) which has been defined by the Commonwealth of Australia (1992) as "using, conserving and enhancing the community's resources so that ecological process, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased". The framework is specifically problem oriented (fisheries in this case). For example, the framework categorises the impact of fishing into effects on humans and the environment. These are subdivided into a hierarchy of a desired level and a procedure comprising of the following steps are applied:

1. Identify appropriate components for the fishery;
2. Specify objectives for components identified;
3. Assess progress with respect to objectives; and
4. Evaluate improvement options.

Many academic institutions (e.g. University of Leeds) have identified that "Effective management of risk is a necessary condition for a sustainable socio-economic-environmental system" (University of Leeds, 2006). Currently, there is no fully integrated sustainability assessment technique (that has been implemented thus far) that uses risk as a tool to sustain any given system. However, other researchers such as Grey and Wiedemann (1999) indicate that risk may be ‘a measure of *un*sustainability”. They acknowledge the differences between the two concepts as given in Table 2.

Table 2: Comparing risk and sustainability (Grey and Wiedemann, 1999)

Feature	Risk (natural science concept)	Sustainability (strong to weak/Agenda 21 concept)
Typical time reference	Short to medium term future	Medium to long term future
Main focus	Focus on loss	Focus on benefits (and system limits)
Uncertainty component	Explicitly calculated	Implicit
Type of potential loss consideration	Mainly human biological/ physical	Environmental, social, economic
Level of analysis of potential loss	To individuals/ groups	To systems (ecosystems/ social systems/ economies)

A number of studies conclude that risk assessment should be used to develop insights rather than for the quantification of results. This is because it is very easy for the results to be misinterpreted by decision makers and stakeholders (North, 1995). However, the communication of risk assessments has progressed since then such that personnel who review the studies are aware of the specific objectives, scope and limitations of the study.

Risk management can be affected by numerous deficiencies but rigorous risk quantification is seen as unnecessary for management purposes. For example, Tweeddale (1992) and Tweeddale and Mehra (1995) attribute the apparent deficiencies in the management of manufacturing risk to be a result of poor understanding of potential hazards; use of poorly designed equipment; lack of proper procedures for maintenance of equipment; limited managerial commitment to organisation; etc. Hence in terms of numerical values, uncertainty will always exist in the assessments. In 1990, Hattis proposed three laws to analyse this uncertainty:

1. “The application of standard statistical techniques to a single data set will nearly always reveal only a trivial proportion of the overall uncertainty in the parameter value”;
2. “Any estimate of the uncertainty of a parameter value will always itself be more uncertain than the estimate of the parameter value”; and
3. “Nearly all parameters distributions look lognormal, as long as you don’t look too closely”.

Researchers such as Murphy (1998) support these laws and have illustrated the validity of the above by providing example cases.

According to Skelton (1996), while methods are available to quantify the probabilities of human error, their validation is problematic, with different methodologies producing different results. This is due to the tangible and intangible nature of risks. Hence excessive reliance on numerical risk assessments can be a significant limitation. Additionally, while it is said that qualitative RA is more effective (McClellan, 2003), the approach suffers from the need for extensive data and can also be difficult to communicate.

2.5.21 INTEGRATED LCA-RA

Fava (1998) states that "LCA provides a framework to achieve better understanding of the trade-offs associated with specific changes in a product, package, or process. This understanding lays the foundation for subsequent risk assessments and risk management efforts by decision-makers". A number of researchers have suggested integration of LCA and RA for various uses such as decision making support for sustainability (Cowell et al., 2002; Shatkin, 2008). The main source of information on practically integrated life cycle and risk assessment can be found in a book by Sonnemann et al. (2004). A comparison of environmental RA and LCA according to Sonnemann et al. (2004) is given in Table 3. The book illustrates the interfaces between the two methodologies via case studies but the authors do not seem to consider the integration as a potential sustainability assessment framework. The aim of the integrated methodology is environmental analysis and decision-making.

Table 3: Comparison of environmental RA and LCA (Sonnemann et al., 2004)

Criteria	Environmental Risk Assessment	Life Cycle Assessment
Object	Industrial process or activity	Functional unit
Spatial scale	Site specific	Global
Temporal scale	Dependant on activity	Product life
Objective	Environmental optimisation by risk minimisation	Environmental optimisation by reduction of potential emissions and resource use
Principle	Comparison of intensity of disturbance with sensitivity of environment	Environmental impact potential of substances
Input data	Specific emission data and environmental properties	General input and output of industrial processes
Dimension	Concentration and dose	Quantity of emission
Reference	Exposure potential to threshold	Characterisation factor
Result	Probability of hazard	Environmental effect score

2.5.22 ECOSYSTEM RESILIENCE

Kaufmann and Cleveland (1995) define ecosystem resilience (or used interchangeably as ecological resilience) as the “magnitude of disturbances that can be absorbed before a system centred on one locally stable equilibrium flips to another”. Arrow et al. (1995) note the significance of ecosystem resilience with respect to carrying capacity where economic activities are considered sustainable only if the ecological systems on which they depend on are also resilient. Ecosystem resilience is seen as a direct measure of ecosystem sustainability however there are some significant issues when measuring ecosystem resilience. There is no agreed method for measuring ecosystem resilience as yet. Furthermore, ecosystem resilience can vary according to the system and according to the type of disturbance it is subjected to.

While a measure of resilience would be beneficial in many ways, the complexity of the variables involved in resilience makes calculation difficult. One of the issues when trying to measure resilience is determining the scope of resilience. According to Carpenter et al. (2001), defining resilience in terms of “resilience of what to what” is significant in attempting to measure it. Temporal, spatial and social scales of measurement also influence resilience and thus resilience is considered to be dynamic (Carpenter et al., 2001). Carpenter et al. (2005) states that resilience cannot be measured directly. However, they propose the use of surrogates (Berkes and Seixas, 2005; Bennett et al., 2005) or proxies which entail the use of resilience mechanisms (Nyström, 2006) such as ecological redundancy, ecological memory, etc. (Brand, 2009). Attributes of these mechanisms may be observed and surrogate resilience is inferred from the observations with the help of models. Other types of resilience surrogates include maintained system identity (Cumming et al., 2005) and percolation theory (Peterson, 2002) as highlighted by Brand (2009).

One prominent approach to surrogate resilience is the threshold approach (Carpenter et al., 2001; Peterson et al., 2003; Bennett et al., 2005) which is based on the following two assumptions:

1. “Ecosystems can shift non-linearly between alternative stable states that are separated by ecological thresholds; and
2. Ecosystem dynamics can be understood by analyzing a few key variables, which is termed the ‘rule of hand’” (Brand, 2009).

The two assumptions are considered to be controversial as their application is not generic but rather specific to different types of ecosystems. For example, the first assumption is controversial because there is empirical evidence showing that while ecosystems can shift between alternative stable states, this occurs predominantly in ecosystems that are controlled by ecosystem adversity as opposed to systems controlled by competing agents within the system (Schröder et al., 2005; Didham, 2006; Brand, 2009). Examples of ecosystems that can shift states due to environmental adversity include the savannah which can alternate between a grassy or woody state. Coral reefs also have alternative stable states where they can alternate between algal-dominated or coral-dominated states (Nyström, 2006) though in this case they are controlled by competition. The second assumption is controversial because it is assumed that key variables that control the system are slow variables (Walker et al., 2004) where the identification of these variables are at best educated guesses and also ignores variability of organisms (Grimm, 1999). Despite these issues, the threshold approach is able to track resilience via the use of bifurcation diagrams (Peterson et al., 2003).

Other attempts to quantify ecosystem resilience include individually modelling or estimating various characteristics of resilience such as inertia, elasticity, amplitude, hysteresis, malleability and damping in collaboration with digital image sensing (Washington-Allen et al., 2008). Methodology to quantify ecological resilience is thus still in its theoretical stages. While there are a number of means to determine resilience through surrogate resilience, the results are estimates and are subject to the assumptions used. However the potential for the use of ecosystem resilience to indicate ecosystem criticality could be a significant step in measuring sustainability.

2.6 CHAPTER CONCLUSIONS

This chapter reviews some of the significant research on sustainability assessment methods as well as tools used for sustainability. There are many types of sustainability assessment methods ranging from EIA driven, TBL types to objective led, principle based types. Numerous sets of sustainability principles have resulted from the various and numerous definitions of sustainability. Numerous indicators have resulted from the attempts to measure progress or impacts according to each principle. Early research in sustainability assessment was based on reconciling the three pillars (weak sustainability) and attempts to incorporate social concerns. Today there are numerous indicators (single and composite) for measuring impacts in the three most relevant systems (environmental, social and economic) from a strong sustainability focus. Most of these indices/criteria measure single aspects of sustainability. Most of the larger and more integrated indicators are aimed at national or global level assessments. The results for many of the methods are complicated and hence difficult to communicate.

Currently research is focussed on improvement of existing techniques via integration of components that have previously been ignored in the respective assessments/indices. There is however a growing understanding that sustainability must be assessed at system levels and especially within the context of complex systems. The primary body of research on systems, resilience and sustainability has been focused on investigating problems and solutions with respect to society's needs concerning development. Most of the work on resilience has been based on ecological resilience but the development on heuristic models to better understand systems is underway. There is still a gap in research in terms of developing ways to stabilise and increase resilience and thus ensure sustainability of Earth systems. Understandably, more information on systems is required but more importantly, methods that consider sustainability in terms complex systems are required.

The next chapter reviews the literature on sustainability assessment from a systems perspective. Complex system theory is reviewed to identify criteria for sustainability of systems. The methods and models introduced in this chapter are then evaluated using the criteria so as to determine whether the methods and models can assess sustainability of complex systems.

CHAPTER 3: EVALUATING SUSTAINABILITY ASSESSMENTS

As concluded from the previous chapter, there are many existing methods and tools for assessing sustainability where each assessment method is based on specific criteria according to the purpose of the assessment. Most existing methods have particular objectives or are designed to assess one or more aspects (e.g. economy, environment, etc) of sustainability. While these methods and models are capable of assessing the chosen aspect of sustainability, they do not seem to have the capacity to assess sustainability holistically. Basically, most assessment methods and models attempt to assess complex adaptive systems via reductionist approaches. While this approach may be useful for dismantling large problems into smaller ones and thereby making the assessments simpler, the assessments end up with a narrow scope, thus limiting the range of sustainability issues that are assessed. This limitation also means that interconnections among systems are neglected and thus the reality of the result is questionable. While ambiguity of the definition of sustainability allows it to be adopted for any given activity and encourages the proliferation of the concept, the significance of what is to be sustained has been somewhat distorted, if not neglected (Robinson, 2004; Lélé, 1991).

It is important to keep in mind the overarching goals for sustainability when assessing sustainability. This is due to the countless angles from which to tackle the issues pertaining to sustainability. Determining the purpose of the assessment and thus what is being assessed and why, is significant (Gale and Cordray, 1994; Parris and Kates, 2003) so as to align the purpose of the assessment with the goals of sustainability. The overarching goal of sustainability is the survival of the human race with all privileges and rights intact (i.e. lives with quality beyond mere biological survival) (Daly, 1973; Brown et al., 1987; Orr, 2002). While this may seem highly anthropocentric, human survival is parallel to the survival of other species since all living things are dependent on the resources of the systems in which they exist (Brown et al., 1987). Given that the systems within the biosphere provide human beings (and other species) with resources and life support (Odum, 1993), damage to these systems would have detrimental consequences (Myers and Knoll, 2001; Tilman and Lehman, 2001). Preventing the collapse of ecological life-supporting systems and the continued survival of human beings (as well as other species) is thus synonymous. Note however that survival of humanity is also dependent on the health of social and economic systems in which technological life supporting systems play a valuable role (Cairns, 2007). Conflicts and inequities have just as much potential to extinguish the human race

(Orr, 2002) as does the damage caused by the technological life supporting systems on which human beings have come to depend upon (Cairns, 2007). Therefore, a holistic and systemic approach may be the ideal solution for sustainability and its assessment.

This chapter focuses on determining basic criteria for sustainability of complex systems and hence determining whether the existing methods and models reviewed in the previous chapter are able to assess sustainability of complex systems. It does this by framing sustainability within the context of complex systems thinking. The result of the analysis shows which existing method and models have the most potential for assessing sustainability from a complex systems perspective and hence which ones, if integrated as a hybrid model, may give the best results for sustainability in practice.

3.1 CHARACTERISTICS OF CAS AND THEIR SIGNIFICANCE FOR SUSTAINABILITY

According to Gunderson and Holling (2002, pp 396), sustainability "is maintained by relationships among a nested set of adaptive cycles arranged in a dynamic hierarchy in space and time – the panarchy". Identifying characteristics of complex systems and how they interact may be useful for sustainability of complex systems (Raskin et al., 2002) because "sustainability is the capacity to create, test, and maintain adaptive capability" (Gunderson and Holling, 2002, pp 403). Furthermore, having an understanding of complex systems is considered to be significant for policy making towards change for sustainability (Munn, 1995). Therefore, understanding the patterns and function of complex systems, and thus making appropriate changes in some areas (e.g. product development (McCarthy et al., 2006) and organisational change (Dooley, 1997), etc.) may help increase resilience and adaptive capacity (Holling, 1996; Gunderson and Holling, 2002; Walker et al., 2004) and aid human survival. Table 4 contains characteristics of complex systems derived from a number of sources. The characteristics in the table help identify the system as being complex and adaptive by indicating the behaviours within the systems. These characteristics are part of the adaptive cycle what is described by Gunderson and Holling (2002) as the "fundamental unit of dynamic change" forming panarchies as described in Chapter 2. The characteristics of CAS need to be addressed or at least acknowledged in order to understand sustainability of the complex system. Following that, they also need to be addressed when assessing sustainability.

Table 4: Characteristics of complex adaptive systems

Characteristic	Description of Characteristic	Reference
Aggregation (Holism)	Complexity emerges from the interactions of agents or systems.	Holland (1992), Arthur (1995)
Nonlinearity	Agents interacting in non-linear ways such that the outcomes of interactions are not proportionate.	Holland (1992)
Randomness	Nonlinearity begets randomness where self-organisation is a result of randomness which is crucial in discovery and new solutions.	Bonabeau et al. (1997)
Flows, local interactions and connectivity	Agents are organised into networks where interactions can trigger other interactions.	Holland (1992), Levin (1998)
Diversity	Agents evolve to fill certain niches and the greater the variety of agents, the stronger the system can be.	Holland (1992), Levin (1998), Kinzig et al., 2002
Emergence	Dispersed interaction of agents acting in parallel result in patters that emerge which informs the behaviour of the agents as well as the behaviour of the system.	Arthur (1997), Holland (1998)
Co-Evolution	Systems are part of the environment and exist within their environment hence as the environment changes, the systems also changes and when the system changes, the environment is also changed.	Kauffman (1980), Ghersa et al. (1994)
No global controller	Controls are provided by competition and coordination between agents.	Kelly (1994), Arthur (1997)
Self-organisation	"Order for free" - there is no command and control hierarchy but there is constant re-organising in order to determine the best fit in the environment in which the system functions.	Waldrop (1992), Kauffman (1980)
Crosscutting Hierarchical interaction	There are many levels of organisation and interaction within systems and units at any level can serve as building blocks of for higher level systems. The interactions are not just hierarchical but can be networks, tangled and crosscutting.	Arthur (1997)
Fractals	Similar patters exist across different levels of systems.	Morales-Matamoros (2010)
Continual adaptation	Individual agents learn and accumulate experience to enable revision of actions for changes in behaviour.	Arthur (1997)
Perpetual novelty	Changes from continual adaptation create perpetual new opportunities.	Arthur (1997)
Edge of chaos/Out-of-equilibrium dynamics	This is the most productive state a system can be in where the system has maximum diversity, connectivity and is able to learn and co-evolve.	Arthur (1997), Langton (1991), Lewin (1992)
Dynamic	Agents and connections are not fixed in time but may be dynamic and change as conditions change. The resulting pattern reflects change, learning and adaptation.	Holland (1995)

Characteristic	Description of Characteristic	Reference
Building blocks or Nested systems	Agents are organised into systems, and small systems are organised into larger systems, i.e. Systems are nested within systems.	Holland (1995)
Simple fundamental rules apply	Agents in a system act according to their own set of local rules – i.e. generative mechanism of a CAS also known as "mini-specks" (Zimmerman et al., 1998).	Nicolis and Prigogine (1989), Eoyang (1997),
Resilience	The capacity to maintain function by absorbing shocks. It is also the ability for renewal and re-organisation.	Gunderson and Holling (2002)
Feedback loops and learning	Systems are able to learn from experience where higher and lower order systems are able to acquire experience from each other.	Arthur (1996)

3.1.1 MULTIPLE AGENTS, DIVERSITY, CONNECTEDNESS, NESTEDNESS, LACK OF ABSOLUTE BOUNDARIES AND LACK OF CONTROLLERS

A complex system has numerous components that exhibit complex interactions. Figure 6 illustrates components of a complex system such as the many diverse sub-systems or agents (represented by the various oval shapes) which interact with each other (Holland, 1992; Stacy, 1995). Examples of agents include atoms, cells, species, individuals, flora, fauna, business units, nations, etc.

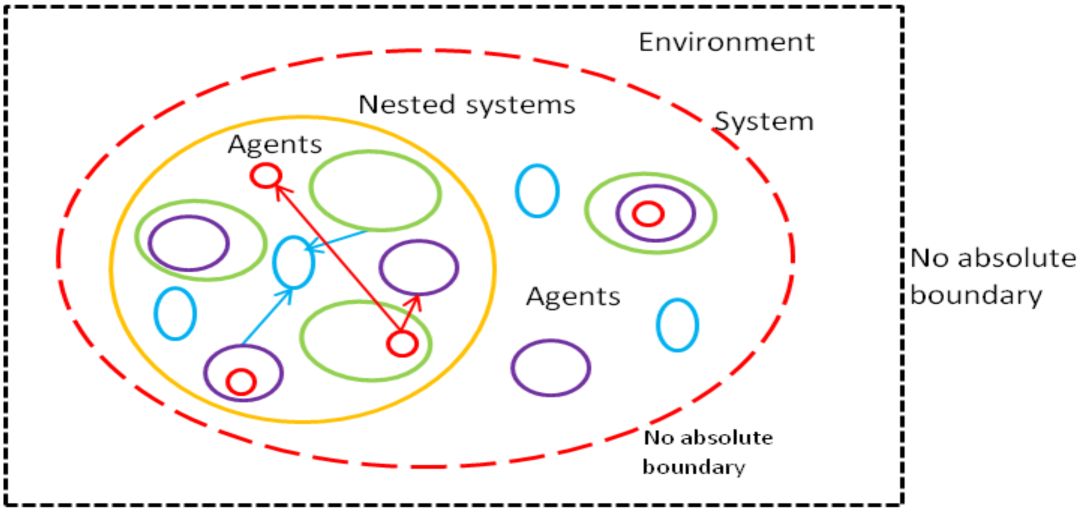

Figure 6: System showing multiple agents, connectedness, nestedness and lack of absolute boundaries

Complex systems may have sub-systems which are themselves complex systems. The smaller lower level systems are nested within larger higher level systems as shown in Figure 7. Examples of sub-systems include the economic sub-system (a lower level or micro-level system) which is nested within the social sub-system (higher level or macro-level system). The social sub-system (lower level system) is nested within the environmental system (higher level system). The smaller systems have faster cycles and are embedded within larger higher level systems with slower cycles and represent the different levels of a panarchy.

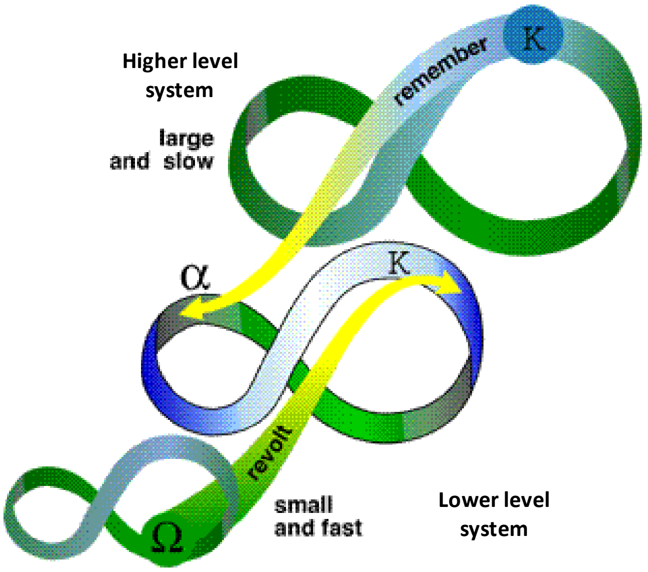

Figure 7: Three system levels of a panarchy together with connections between them (slightly modified from Holling (2004))

Each system agent may be governed by a simple set of rules. The agents are semi-autonomous and their collective interactions result in the complex behaviour exhibited by the whole system (Kurtz and Snowden, 2003). For example, there any many types of ants in an ant colony, each with differentiated functions. However, they all work together for the survival of the entire colony. The different types of ants depend on each other to some extent, and likewise, agents in a complex system may also depend on each other (Lichtenstein, 2000). Interactions among agents and sub-systems may lead to short or long term changes in the behaviour of the overall system (Bennet and Bennet, 2004). Changes in the system may in turn affect the agents within the system, the micro-level systems which are nested within system, or they may change the macro-level system and the environment in which the system exist.

Due to the number of agents, sub-systems, interconnections and interdependencies of complex systems, it is difficult to identify boundaries. Therefore, complex systems are open systems where energy and information are able to move within and across different system levels. System boundaries are thus subjective and depend on the observer. According to Cilliers (2001), complex systems such as organizations are given boundaries "to determine the identity of the organization". While there are boundaries, they are "not clearly defined in their nature or their place". He quotes Zeleny (in Khalil & Boulding, 1996 p. 133) as follows:

> "All social systems, and thus all living systems, create, maintain, and degrade their own boundaries. These boundaries do not separate but intimately connect the system with its environment. They do not have to be just physical or topological, but are primarily functional, behavioural, and communicational. They are not "perimeters" but functional constitutive components of a given system."

Thus while it is possible to set a boundary, that boundary is not absolute but subjective for a specific observational purpose.

3.1.2 NONLINEARITY, DYNAMIC NATURE OF SYSTEMS, CHAOS AND PREDICTABILITY

According to Eisenhardt and Bhatia (2002), linear systems are highly structured and coupled leading to high predictability, high efficiency but low adaptability. Unlike linear systems with directly proportional cause and effect relationships, nonlinearity means that a change can lead to disproportionate effects (butterfly effect), proportional effects or even no effect at all. This leads to a contrast between Newtonian science and complexity (Holland, 1975; Gleick, 1987; Wheatley, 1992; Lichtenstein, 2000). The non-linear nature of the system results in non-linear dynamics and thus the system is unpredictable (Pascale, 1999; Bennet and Bennet; Dent and Holt, 2001). According to Peitgen et al. (1992), prediction becomes fruitless as error grows exponentially into the future. While the system may be unpredictable, some patterns can be determined via modelling (Hansell et al., 1997). For example, mathematical climate models have been instrumental in understanding nonlinear dynamic systems (Lorenz, 1963). They have shown how the nonlinear dynamic nature of systems may lead to different patterns of behaviours and different states of equilibrium. For example, chaos results when random behaviours occur in deterministic systems as controlling parameters pass through a threshold value (Ott, 1993).

CAS are nonlinear but they are not chaotic. They lie between linear and chaotic systems and thus the level of connectivity among agents and their interactions result in phenomena that are not fully controlled or arbitrary (Brown and Eisenhardt, 1997; McCarthy et al., 2006). Nonlinearity and the dynamic nature of the CAS lead to systems that best fit the environment at a given time where evolution via emergence and adaptation occurs at the edge of chaos (Kaufman, 1993). The edge of chaos is said to be the most productive state of a system where it has maximum diversity, connectivity and is able to learn and co-evolve (Arthur, 1997; Langton, 1991). In terms of their dynamic nature, complex system change with time (Lichtenstein, 2000). The nature of the changes depend on the active agents, their interconnections, feedback loops, past experiences, as well as behaviours that emerge from all the interactions inside and outside of the system.

3.1.3 FEEDBACK LOOPS, MEMORY, SELF ORGANISATION, EMERGENCE AND CO-EVOLUTION

Figure 8 illustrates the mechanism for self-organization, emergence, complex adaptation and feedback loops in a complex system. As mentioned previously, different agents can have different functions and different sets of rules to govern the functions. Interactions, inter-relationships and connectivity among multiple and diverse agents lead to self-organisation (Kauffman, 1993; Kauffman, 1995), emergence and the capacity to evolve (Rammel and Staudinger, 2004).

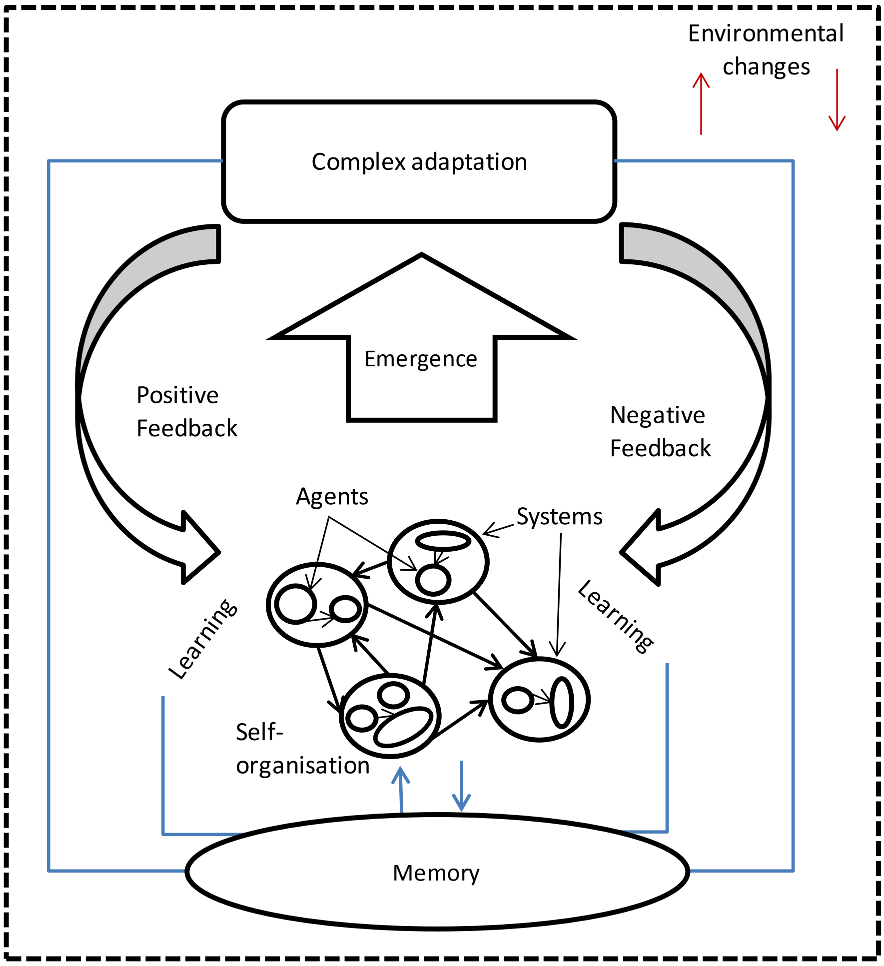

Figure 8: Function of feedback loops, memory, adaptation, self-organization, emergence leading to co-evolution (modified from Wikipedia (2010))

Multiple and diverse agents interact with each other seemingly randomly (i.e. no central controllers within the system) where the agents self-organise to best fit their environment. Collectively, order emerges at the macro-level resulting from this randomness and as result of achieving the best fit. The emergent phenomenon are global (i.e. observed at the macro-level), ostensive (i.e. properties show themselves), novel (previously unobserved features), dynamic (new attractors evolve over time) and depict coherence or correlation (maintains a sense of identity and shows unity of lower and upper level components) (Goldstein, 1999). Due to the multitude of interactions, emergence and the emergent properties are unpredictable across different system levels. Furthermore, according to Holland in Khalil and Boulding (1996, p 145), "complex adaptive systems are constantly revising and rearranging their building blocks [agents] as they gain experience".

In complex systems, the environment in which the agents exist undergo changes. These changes occur because the environment itself is a level in a nested system, and thus, is subject to changes influenced by its environment, yet another level in the nested system. Co-evolution occurs as a result of changes within the system and also in the system's environment. I.e., interactions among agents within the system may change the environment in which the system functions. Since the system is part of the environment, changes to the environment would trigger changes to the system. Subsequently, there is constant change in the system and its environment.

The agents within the system are able to fit in the environment via adaptation where adaptation occurs in response to changes within the system (adapting to other agents – self organizing) as well as due to changes from environmental changes. While there are no central controllers to guide change, systems are able to learn and adapt from previous experiences. This experience is a result of learning enabled via negative and positive feedback where systems can retain the memory from past experiences. The main drivers for adaptation and learning are competition and cooperation among agents to fit in the environment. The information required is disseminated via the vast interconnections among the agents, sub-systems, etc. in a system.

As mentioned, agents are semi-autonomous as they have their own set of rules but these rules are subject to change due to adaptations resulting from changes in the agent's environment. Dimensionality is the degree of freedom an agent has with respect to autonomous behaviour (Choi et al., 2001). Negative and positive feedback loops are a fundamental mechanism of CAS as they influence dimensionality and thus can radically affect how the system functions. For example, negative feedbacks limit dimensionality by limiting the agent's behaviour. Conversely, positive feedbacks lead to higher degrees of autonomy in agent behaviour and thus increasing dimensionality of successful systems, behaviours and agents. Self-organisation, emergence, adaptation, and co-evolution have no central controllers (Capra, 1982), no planning or managing. It is a matter of constantly re-organizing to find the best fit within the system and the environment.

3.1.4 LIMITS, RESILIENCE AND ADAPTIVE CAPACITY

As discussed in the literature review in Chapter 2, much work has been done on the concept of resilience and adaptive capacity where both are significant properties of complex systems, CAS and sustainability (Arrow et al., 1995; Berkes and Folke, 1998; Adger et al., 2001; Gunderson and Holling, 2002; Folke, 2006). As mentioned previously, there are two meanings of resilience, one applicable to engineering, and the other applicable to ecosystems:

- **Engineering resilience** – "the rate at which a system returns to a single steady or cyclic state following a perturbation" (Gunderson et al. (2009) according to Holling (1996)); and
- **Ecological resilience** – "A measure of the amount of change or disruption that is required to transform a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures" (Gunderson et al. (2009) according to Holling (1973)).

The two types of resilience are contrasting as engineering resilience focuses on maintaining efficiency of function while ecological resilience is focused on maintaining the existence of function (Holling and Gunderson, 2002). The second instance of resilience, ecological resilience, is more significant for the goal of sustainability and fits within the context of this research. The two doctrines differ in the way they view stability and points of equilibrium. Engineering resilience assumes there is only one state of equilibrium and if there are others, they can be avoided in order to reduce complexity. Conversely, in ecological resilience theory, multiple states of equilibrium that determine different functional states exist. The significance of this difference is that ecosystems can have multiple points of resilience per function (Ascher, 2001) where changes to systems can occur gradually or as surprise regime shifts (Folke et al., 2002).

Note that the capacity for re-reorganisation and renewal are also components of resilience (Berkes et al., 2003; Folke, 2006)

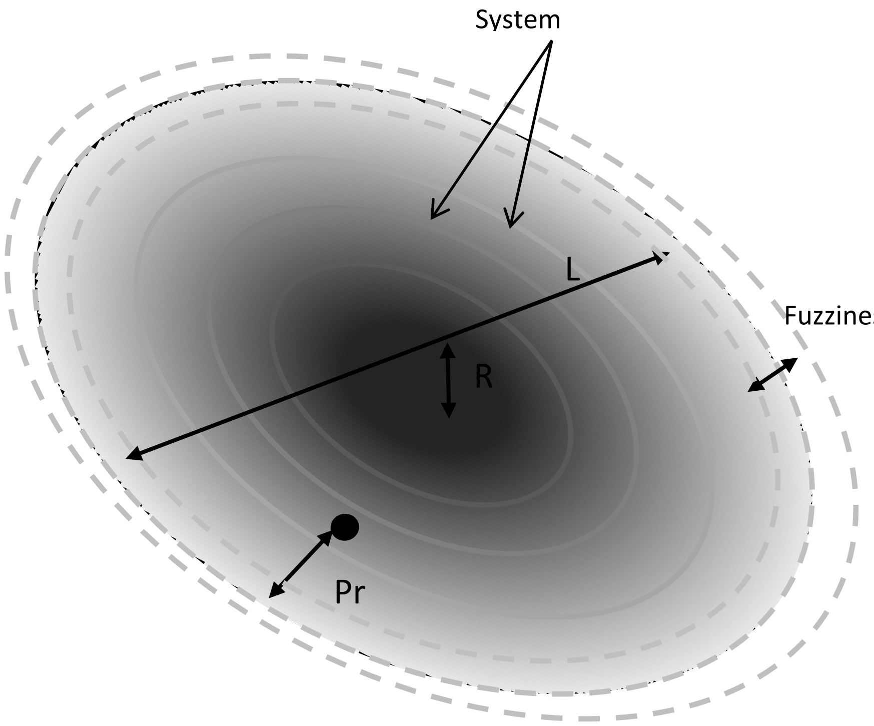

Figure 9: Attributes of resilience (modified from Walker et al. (2004))

According to Folke et al. (2002), “resilience-building increases the capacity of a social-ecological system to cope with surprise”. Walker et al. (2004) describes three significant attributes of resilience: Latitude (similar to limits or thresholds); Resistance; and Precariousness (Figure 9). Latitude (L), hereafter referred to as limit or threshold, is the maximum change the system can undergo without losing its ability to recover. The fuzziness marks a zone of uncertainty which according to Rockström et al. (2009) is a result of:

1. The lack of scientific knowledge concerning biophysical thresholds;
2. Lack of understanding regarding complex behaviour of systems such as feedback mechanisms; and
3. “Uncertainty regarding the length of time between overshoot of a critical control variable and when a threshold is crossed” (Rockström et al., 2009).

The last reason for uncertainty exists on the premise that there will be overshoot at some point in time due to the dynamic nature of a system. The impact of this would depend on whether or not the system is able to return to its previous state and hence avoid a regime shift or collapse as function is lost. Meadows et al.'s (1972, 2004) limits-to-growth is one attempt at identifying system limits.

Resistance (R) refers to the effort required to change the system and precariousness (Pr) refers to the proximity of the current system from the limit or threshold. These three attributes of resilience are influenced across scales by the systems above and below it (Walker et al., 2004). This can be explained using the adaptive cycle and the panarchy metaphor as described by Holling and Gunderson (2002). The adaptive cycle consist of the exploitation or growth (r), conservation (K), release (Ω), and reorganization (α) phases where cycles are nested hierarchically across time and space (Gunderson and Holling, 2002). Adaptive capacity is linked to the loss of resources (potential), connectivity and resilience as shown in the heuristic model in Figure 10.

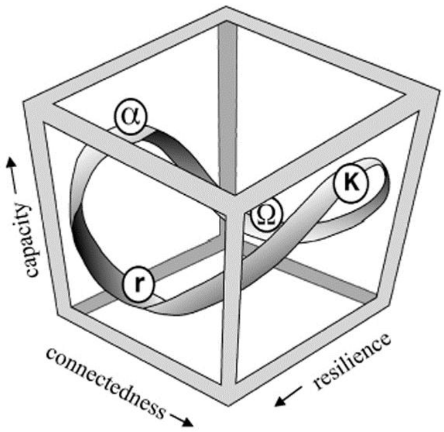

Figure 10: Heuristic model of the adaptive cycle. Reproduced from Allison and Hobbs (2004)

The ability to control or change limits, resistance, precariousness and system dynamics across levels in a panarchy is considered to be a measure of adaptability (Walker et al., 2004). Since most activity in the biosphere is dominated by human actions, adaptability is largely a function of the social component (Berkes et al. 2003). Adaptability and resilience are fundamental properties of sustainability or as Odum states:

> "The real world is observed to pulse and oscillate. There are oscillating steady states. If the oscillating pattern is the normal one, then sustainability concerns managing, and adapting to the frequencies of oscillation of natural capital that perform best. Sustainability may not be the level steady state of the classical sigmoid curve but the process of adapting to oscillation."

3.1.5 HOLISM

It is not possible to understand a complex system just by analysing each of its components separately (individual agents or sub-systems) (Lichtenstein, 2000; Dent and Holt, 2001). When it comes to organisations such as businesses, sustainability needs to be more than the economic or the environmental systems that are traditionally focussed upon. The concept of strong sustainability gives a more holistic view of the components that need to be included. Together with this viewpoint, various and numerous subsystems also need to be considered for holism. For example it should be understood that economy is a subset of society as are business, community, etc. Complex systems have many components and there are many levels of interconnections and interdependencies among agents and different system levels. Any one of these agents, interconnections and interdependencies may cause surprises in the system and hence must be taken into account when assessing sustainability. In addition to the inclusion of many levels of interconnections, multiple views of sustainability with respect to stakeholders need to be taken into account.

The dynamic and nonlinear interactions of low-level agents lead to the emergence of macroscopic patterns. These macroscopic patters are more than the sum of the individual agents thus traditional reductionist methods fail to describe the overall macroscopic pattern. Holistic approaches that relate the simple interactions and rules of the individual agents to that of the entire system as well as emergent properties may provide better understanding of the adaptive system. The different levels described by Marshal and Toffel (2005) pertaining to the different systems (economy, society and environment as systems) may enable a holistic assessment of sustainability as these levels encompass the core objectives of sustainability. Marshal and Toffel (2005) outline four levels of issues pertaining to sustainability. These levels may provide a useful focus for assessment albeit from a "preventing unsustainability" perspective where the purpose of the assessment is to prevent or mitigate:

1. Actions that, if continued at the current or forecasted rate, endanger the survival of humans (Level 1);
2. Actions that significantly reduce life expectancy or other basic health indicators (Level 2);
3. Actions that may cause species extinction or that violate human rights (Level 3); and
4. Actions that reduce quality of life or are inconsistent with other values, beliefs, or aesthetic preferences (Level 4).

Considering that the goal for sustainability is the survival of humans, preventing unsustainability appears to be synonymous. Making these levels applicable for evaluating sustainability would require all system levels and interactions to be taken into account thereby enabling a holistic sustainability assessment.

3.2 EVALUATING EXISTING SUSTAINABILITY ASSESSMENTS

Human systems, or socio-ecological systems, are complex (Carpenter et al., 2001; Folke et al., 2002; Cummin and Collier, 2005; Fiksel, 2006) and adaptive (Gunderson and Holling, 2002) and hence have the characteristics discussed previously. In order to assess a complex system, its characteristics need to be understood. This section focuses on determining whether existing sustainability assessment methods and models are able to assess sustainability of complex systems. In order to do this, a number of criteria and sub-criteria for evaluating the assessments are proposed. The characteristics pertaining to the properties of CAS can all be considered as a fundamental criterion. In addition to complexity as a criterion, sustainability assessment may need to account for other significant components as well.

Many researchers have stated that in order to assess sustainability, it is essential to have an idea of what sustainability is and what is being assessed (Pope et al., 2004; Paris and Kates, 2003). The WCED (1987) definition for sustainable development can provide a number of key criteria applicable to the sustainability of complex systems. For example, the concept of needs and meeting needs; intergenerational and intra-generational wellbeing; and the concept of limitations can be considered among significant characteristics for sustainability. These characteristics relate to time and space dimensions of systems (Costanza and Patten, 1995); the exchange of resources in terms of inputs and outputs within and between different agents and systems; and limitations imposed by the environment. Since these elements are also part of the characteristics of complex systems, they can be considered under the complexity criterion for evaluating sustainability assessments. Furthermore, there is one additional criterion that needs be considered for the purpose of ensuring the assessments are scientifically based rather than opinion based. This criterion is based on available criticisms of methods and their disadvantages as given in Chapter 2.

3.2.1 CRITERIA FOR EVALUATING SUSTAINABILITY ASSESSMENTS

An assessment method that is to be used to assess sustainability of complex systems should:

1. Take complexity of the system into account which then requires the following characteristics and properties of complex systems to be taken into account:
    a. Multiple agents, diversity, connectedness, nestedness, lack of absolute boundaries and lack of controllers
    b. Nonlinearity, dynamic nature of systems, chaos and predictability
    c. Feedback loops, memory, adaptation, self-organisation, emergence and co-evolution
    d. Limits, resilience and adaptive capacity
    e. Holism
2. Be based on science where appropriate. It may be worthwhile to identify some of the basic elements – laws of physics, chemistry, thermodynamics etc.

From the review of existing methods and models carried out in Chapter 2, it is obvious that some characteristics of complex systems, such as memory, adaptation, self-organisation, emergence and co-evolution are not considered by any of the existing methods and models. Since it is known that these characteristics are not considered, they can be left out from the evaluation process for the time being. This leads to a simplified set of criteria using the most basic characteristics of complex systems.

1: How to determine whether complexity is taken into account

Now that the criteria for evaluating the sustainability assessments have been determined, the next step is to determine how to evaluate the methods and models identified in Chapter 2 using these criteria. Using the literature available on the methods and models as reviewed in Chapter 2, a two-step approach can be used to evaluate them:

Step 1: Identify the goal or purpose of the model's intended use; and

Step 2: Identify the methodological framework used by the respective assessment and evaluate them by asking a number of questions that reflect the properties of each criteria.

In order to assess sustainability of a complex system, the assessment method or model should:

1. Take complexity of the system into account by:
    a. Recognising the existence of multiple agents and system levels;
    b. Recognising interconnections and interdependencies;
    c. Taking system dynamics into account (time and space);
    d. Recognising system limits or thresholds;
    e. Recognising resilience and adaptive capacity; and
    f. Being holistic; and
2. Be based on science where appropriate.

Identifying the goal or purpose of the assessment would highlight the agents, the systems and subsystems that are assessed by the model. It would highlight the boundaries with respect to what is assessed and the scope and extent to which the assessment is carried out. For example, the Ecological Footprint assesses biophysical sustainability; however, it still fails to include some significant aspects such as pollution in its assessment. Furthermore, it does not take the socioeconomic systems into account nor does it recognise the interconnections among systems. This would mean that the Ecological Footprint fails to be a holistic assessment. The evaluation is carried out by answering a number of simple questions regarding the ability of the assessment models to meet the criteria defined. The questions for each criterion are given as follows.

A. Recognise the existence of multiple agents and system levels

Many assessment methods and models concentrate on assessing particular components of systems. In order to assess sustainability of complex systems, the assessment should take the agents of the system as well as the different levels of the system into account. For example, indicator based methods such as Wellbeing Index caters for the social component of sustainability by taking numerous subsystems that make up the social system into account. However, it fails to consider different systems levels (economic and environmental). The idea that systems are nested within each other and that the social system is a part of the larger higher level (biophysical) systems is not something that is taken into account by the Wellbeing Index thus it fails this particular criteria for complex systems.

Questions to ask:

- Does the assessment take a systems perspective?
- Does the assessment assess multiple systems?
- Does the assessment include the assessment of multiple agents?

If the answer to any of these questions is a "no", then it can be considered that the assessment does not recognise multiple and diverse system levels and agents as part of the sustainability assessment.

B. Recognise interconnections and interdependencies between systems assessed

Interconnections and interdependencies are inherent characteristics of complex systems. Since the interconnections and interdependencies govern the function of the system, they need to be acknowledged and explored in order to understand how the system is operating and whether it is operating in a natural stress free manner. A sustainability assessment should be able to map or recognise a network of relevant impacts and their sources to indicate the cause and effect as thoroughly as possible.

Questions to ask:

- Does the assessment acknowledge the interconnections and interdependencies among systems and agents?
- Does the assessment explore the impacts from the interconnections among systems and agents?

If the answers to the above questions are a "no", then it can be considered that the assessment does not account for the interconnections among components of a complex system.

C. Take system dynamics into account (time and space)

Complex systems are dynamic and hence change with time and space. Human activities are capable of influencing some changes and the rates of these changes, either as a conscious effort guided by policy or as an unconscious result of some action. In nature, systems evolve across time and space by sacrificing weaker components to enable sustainability of the whole.

Information on how system components are behaving can be useful for positively influencing them.

Time

A major concern of sustainability for society is the provision of needs for the present as well as for the future. In addition, one of the issues for sustainability has been the duration for which some action should be sustained. This is closely linked in with the question of "what should be sustained?" In terms of assessments, the goal is to determine impacts with respect to whether they occur currently or whether they will affect the future. While current impacts are observable and hence may be measured, future actions on the environment are unknown. However, information that could assist future decision making would be desirable even though the future itself is unpredictable. While the future may be unpredictable, the objective of science and assessments is to understand impacts (where they are coming from, what they affect, how they affect different systems, how they change with time, etc.) and thus help formulate ways of predicting certain behaviours of systems. In terms of systems and predictions, emergent behaviour of complex systems renders predictions almost impossible. Emergent behaviour is dependent on historical events (Hubler, 2005; Kelso, 2005), the interacting agents concerned, as well as how the existing agents would self-organize leading to the emergence of particular system behaviour. Nevertheless, knowing about the past does not mean the future will be predictable and this is due to other properties of complex systems such as nonlinearity, interconnections and diversity of agents, subsystems, etc. However, past and current events can provide data essential for mathematical modelling of potential futures.

Space

Most assessments were developed with the aim of assessing a particular aspect of sustainability. These may have been framed with local/regional or global impacts in mind. Sustainability of complex systems depends on both local and global effects and thus both local and global effects need to be accounted when assessing sustainability. There are some effects, such as photochemical oxidation, eutrophication, etc., which are more significant at a local level where the local populations, species and resources are affected. Likewise, there are effects such as global warming that are more significant at a global level and affect larger and diverse populations of species and systems.

Additionally, there are systems which may thrive in a local setting while adverse effects are only seen globally. A good example of this is the economy improving locally while globally, the environment is deteriorating due to pollution (Arrow and Bolin, 1995). It would seem that global impacts are more significant for the biosphere in the long term while in the short term, local or regional impacts are felt more immediately. Therefore, both local and global effects need to be considered during assessment where the assessment should be able to identify the spatial dimensions that could be affected by particular impacts. The main factor is that the parameters for each local system are unique to that system. This means that changes which may be within tolerance for one location may not be for another (and even within an area, micro effects may be found). The idea of unique levels of tolerance per system (location) is significant. It may also seem obvious but it is often overlooked.

Questions to ask

- Does the assessment take time and space into account?
- Does the assessment model system dynamics?
- Does the assessment allow future projections via modelling?

If the answers to the above questions are "no", then it can be considered that the assessment does not take system dynamics into account.

D. Recognise system limits or thresholds

As discussed previously, the concept of limits is a significant part of sustainability of systems. Complex systems, while being capable of adapting, still have certain limits, thresholds or boundaries within which they function. There are tipping points beyond which the system would move into different system configurations i.e. regime shift (Walker and Meyers, 2004) depending on the resilience and adaptive capacity of the system (Gunderson and Holling 2002; Allison and Hobbs, 2004). A panarchy can consist of a number of CAS hierarchically connected. Different system levels have different limits where they vary according to the function of the system, available resources and other parameters that affect the function of the system.

Furthermore changes at the individual level may be insignificant if only a few individuals change; however, even minor changes, if made by all individuals, can have significant effects at the system level. When a lower level system collapses, it may cause a cascading effect of collapse in neighbouring systems at both higher and lower level. The higher level systems are likely to be affected if they are not resilient or able to adapt. When a system collapses, the agents within it may reorganise leading to natural renewal where the system may or may not retain its original function. Renewal entails reorganising and functioning within new boundaries and may not necessarily be a disadvantage since this is the basis of evolution. However, attempting to sustain unsustainable practices, i.e. attempting to sustain a faster smaller cycle of a lower level system (such as a business system) that damages other systems, may degrade and endanger higher level systems in a panarchy.

Human survival would benefit if life supporting systems are not adversely affected by reorganisation at higher order system levels. Fiebleman (1954, p. 61), founder of Fiebleman's theory of integrative system levels stated that "for an organism at any given level, its mechanism lies at the level below and its purpose at the level above". If human existence is the goal of sustainability, then the purpose at the system level above would be to ensure the environment or the biosphere is capable of supporting humans. However, it should be noted that mechanisms below may not necessarily lead to sustainability above and with time systems limits may be reached and lead to the collapse of the panarchy.

Questions to ask

- Does the assessment attempt to identify limits of systems?
- Does it take into account limits that are relevant to the goal of sustainability?

If the answers to the above questions are "no", then it can be considered that the assessment does not recognise system limits or thresholds.

E. Recognise resilience and adaptive capacity

As mentioned previously, resilience is a significant dimension of complex systems and especially significant for system sustainability. Resilience is defined as "[…] the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour" (Holling and Gunderson 2002: 4). Many of the other characteristics of complex systems (e.g. diversity) affect resilience. If resilience is reduced, the system becomes increasingly vulnerable to external events (Alexander 2000). If the system becomes vulnerable, small disturbances may be enough to cause large consequences (Adger, 2006). The system's capacity to sustain natural resources may be affected and this may in turn adversely affect ecosystem services for society (Folke at al., 2004). While resilience is advantageous to maintain significant ecosystem functions, it is important for lower level systems to renew themselves in order to prevent deterioration of higher level systems and themselves contradiction to above section. One example of renewal as a mechanism for system stability include the Everglades and forest fires (Holling 1986; Gunderson,1994) where delays in fires resulted in higher biomass accumulation which when burnt, destroys more components of the system than an earlier fire would have, which is not necessarily beneficial for that forest system. Another example is the effect of drought in locations with multiple sources for water supply as compared to locations with single reservoir systems.

It would be an advantage if sustainability assessments are able to provide some indication of resilience as resilience offers a buffer, at least in terms of being informative of potential collapse of systems, and thus may allow the ability and perhaps time to be innovative. In this case, as with limits and thresholds, the methodology and the final output of the assessment can be examined to determine whether the results give indication of resilience.

Questions to ask

- Does the assessment provide a way to measure resilience?
- Do the assessment results provide indication of resilience?
- Does the assessment give indication of the adaptive capacity of the system/s?

If the answers to the above questions are “no”, then it can be considered that the assessment does not recognise system limits or thresholds.

F. Be holistic

Holistic assessment is synonymous with completeness of assessment. As mentioned in previous chapters, reductionist approaches, while being user-friendly (Costanza (2000), tend to attempt understanding of systems by understanding components of systems. However when it comes to complex systems, a part cannot contain the whole. Since a part of the system cannot determine the behaviour of the entire system, the entire system should be considered which includes how complexity is generated and how changes in one system affect another. Thus impacts on lower level systems as well as impacts on the higher macro level systems need to be investigated and analysed when assessing sustainability. Assessment of a single system level is not sufficient and thus sustainability assessment must be broadened to include the social, environmental and economic systems while considering the interactions at the same time (Fenner et al., 2006). It must take into account the relevant systems which are affected rather than attempting to prescribe the behaviour of the whole via determining the behaviour of a few system elements. Reductionist approaches fail to measure sustainability since they only measure one or a handful of dimensions pertaining to sustainability. The assessment thus need to be examined to determine if they only cater to one aspect of sustainability or attempts to take a more holistic approach.

Questions to ask:

- Is the assessment based on reductionist approaches? (I.e. do they attempt to explain sustainability of the whole by assessing the sustainability of a few aspects of the system?)
- If there is integration of the different subsystems of sustainability, does it consider the interconnections among them?

For this to be answered “yes”, the three systems (social, environment and economy) as well as interconnections among them need to be explored in the assessment.

2: Be based on science where appropriate.

Sound science needs to be the basis of any methodology when considering systems, interactions and sustainability. Science can help prevent subjectivity that may distort the results. If the results are to be distorted, it may lead to unsustainability rather than the sustainability that is sought. This criterion is thus useful for ascertaining whether the method evaluated meet the basic requirements for scientific validity and reliability. Scientific methods are used to investigate and acquire knowledge where scientific thinking is based on empiricism, rationalism (logical reasoning) and scepticism. Scientific methods are characterised by iteration (Brody, 1993), recursion, interleaving (Jevons, 1874; Godfrey-Smith, 2003) and vigorous procedure (Wilson, 1952) consisting of:

- Characterisation (or observation) of phenomenon;
- Formulation of hypotheses;
- Prediction of other phenomenon based on the hypothesis; and
- Performing experiments of the predictions.

According to the National Research Council (2001), “the credibility of the results depends on adherence to established scientific practices. Scientists are trained to be sceptical of established dogma, and complete unanimity is thus unlikely. Nevertheless, ongoing review of the results and of subsequent work helps establish when a broad consensus exists, when competing theories remain controversial, and when evidence is speculative”. To this end, reliability and validity are significant requirements for scientific methods (Kimberlin and Winterstein, 2008) and are “ways of demonstrating and communicating the rigour of research process and the trustworthiness of research findings” (Roberts et al., 2006).

LoBiondo-Wood and Haber (1998, p. 558) define reliability as “the consistency or constancy of a measuring instrument”. According to Kirk and Miller (1986), there are three types of reliability based on: 1. Repeatability or the degree to which the result remains similar; 2. Temporal stability which is consistency of results after a given time period; and 3. Similarity of measurements across observers – changing the observer does not affect the result. In order for a method to be reliable, the results are to be testable and repeatable over time and across observers. Reliability is considered to be necessary for validity (Shuttleworth, 2008) though according to Roberts et al. (2006) it is insufficient for validity. Validity establishes whether the method meets the scientific research method requirements. More specifically, validity is defined as “the extent to which an instrument measures what it purports to measure” (Kimberlin and Winterstein, 2008). The authors also state that an instrument can be reliable without being valid. Validity is measured internally and externally (Punch, 1998; Roberts et al., 2006). The three main aspects of internal validity according to Punch (1998) and Long and Johnson (2000) are:

1. Content validity - “degree to which the entirety of the phenomenon under investigation is addressed” (Long and Johnson, 2000, p31);
2. Criterion-related validity - correlation between measured performance and actual performance (Long and Johnson, 2000, p32); and
3. Construct validity – “consideration of the proximity of the instrument to the construct in question” (Long and Johnson, 2000, p32).

While internal validity is related to the reasons behind the results, external validity concerns the ability to generalise or apply the results to other cases. External validity deals with the applicability of the results according to representation of samples (Roberts et al., 2006).

The above definitions and aspects of reliability and validity are primarily for quantitative methods (positivist paradigm). While they can apply to qualitative research (constructivist paradigm) in terms of methodological vigorousness, the results may not be repeatable or similar. This is because methods relying on human judgment can suffer from lack of reliability as different participants would have different viewpoints leading to different results (Hunter and Schmidt, 1990; Hammersley, 1992). The need for reliability and validity in qualitative research lead to the idea that "qualitative research should be judged against a different set of standards, using alternative set of strategies to quantitative research" (Roberts et al., 2006). As such, different terminology and definitions relating to reliability and validity have been developed. Examples of work proposing alternative definitions include Sandelowski (1986), Lincoln and Guba (1985) and Robson (1993) who favour the term "dependability" over reliability, and Lincoln and Guba (1985) who use the term "credibility" to replace validity. Furthermore, researchers such as Brink (1991) proposed stability (consistent answers at different times), consistency (integrity of issues so the responses are concordant) and equivalence (use of alternative forms of the questions in the same interview) as means for reliability of qualitative work.

Irrespective of the terms given to describe the requirement for reliability and validity, the idea remains that research and methods need to be sound in order to prevent misleading action in the real world. Therefore, the criterion for science in this thesis requires the existing methods and models to have been developed within guiding principles for scientific inquiry. Most of the fundamental principles for scientific methods remain similar despite their qualitative or quantitative nature. Therefore, a set of common principles such as those given by Towne and Shavelson (2002, p52) are considered to be suitable for evaluating methods in this research:

- "Pose significant questions that can be investigated empirically;
- Link research to relevant theory;
- Use methods that permit direct investigation of the question;
- Provide a coherent and explicit chain of reasoning;
- Replicate and generalize across studies; and
- Disclose research to encourage professional scrutiny and critique".

Additionally, the evaluation of sustainability assessments in this study relies on existing critiques of techniques where the criticisms are related to science rather than their methodological disadvantages. An example of a method which is considered scientifically suspect by some scholars is The Natural Step (Upham, 2000). According to Broman et al. (2000) TNS is based on the Second Law of Thermodynamics or specifically the Law of Entropy. However, according to Hammond (2004), TNS uses the Laws of Thermodynamics only as a metaphor where the Entropy

Law used is generic and ill-defined. Thus Upham (2000, pp. 187) states that TNS suffers from a "lack of an explicit demonstration of the links between its 'basic science', and the principles themselves". The following questions are used to determine whether there are issues with the science behind the assessment methods and models.

Questions to ask:

- Does the literature support the science in the method or model of assessment?
    - Is the science behind the methodology under criticism?
    - Is the methodology indifferent to fundamental scientific laws?
    - Are basic requirements for scientific reliability and validity investigated?

If the answer to any one of the questions is a "no", then the result for that assessment method is that it is not based on science where appropriate. I think you could be more specific than this; validity of data, sources of data, independent verification of results, preservation of basic scientific laws and principles etc.

3.2.2 EVALUATING THE ASSESSMENTS

Using the criteria from the section above, the assessment methods and tools reviewed in Chapter 2 are evaluated with the results presented in Table 5. Each parameter is given equal weighting since the goal of the evaluation is to determine if the assessment methods and models contains aspects of the criteria identified for complex systems. The assessments with the highest scores are considered to be potential candidates for a new model for assessing sustainability of complex systems.

Table 5: Evaluating existing methods and models used to assess sustainability

Indicator	Type of tool	Description/purpose	Multiple Agents/systems	Dynamics	Interconnections, interdependencies	Limits	Resilience	Holistic	Science	Score
					Basic analytical methods					
Emergy	Biophysical model, Analytical	Defined as "the available energy of one kind that has been previously used up, directly and indirectly, to make a service or a product and its unit is the emjoule. Thus is essentially the total amount of energy required to produce a product or carry out a service	No	No	No, only a calculation based on fundamental law	No	No	No	Yes	**1**
Exergy	Biophysical model, Analytical	Defined as "the maximum work that can be extracted from a system when this system moves towards thermodynamic equilibrium with a reference state"	No	No	No	No	No	No	Yes	**1**
					Integrated methods					
Triple Bottom Line	Accounting	A sustainability accounting method used to account for an organisation's environmental, social and economic impacts (bottom lines)	No	No	No	No	No	Integration of 3 systems but still Reductionist	No	**0**
The Natural Step	Principles, objective oriented	A principle based framework that is used for environmental management for strategic decision making	Yes	No	No	No	No	No	No	**1**
Sustainability assessment by fuzzy evaluation (SAFE)	Analytical	Is a method for assessing the sustainability of nations resulting in a measure through the use of indicators for environmental integrity, economic efficiency and social welfare	Yes	Yes	No	No	No	No	Yes	**3**
Ecosystem Resilience	Ecological indicator	Is the "magnitude of disturbances that can be absorbed before a system centred on one locally stable equilibrium flips to another".	No	Yes	No	Yes	Yes	No	Yes	**4**
Barometer of Sustainability	Social and Ecological indicators, Analytical	Evaluates sustainability of the three systems simultaneously while keeping the sustainability of human and ecological systems calculations separate	No	No	Yes - Takes system perspective	No	No	Reductionist through integration	Yes	**2**
Ecological Footprint	Biophysical model	Is based on the carrying capacity concept where instead of measuring the number of people that can be supported per given amount of land, it attempts to determine the amount of land (resources) required to support a defined population on an indefinite basis	No	No	No, only considers the biophysical and even then ignores significant aspects such as pollution	Yes	No	No	Yes	**2**

Indicator	Type of tool	Description/purpose	Multiple Agents/systems	Dynamics	Interconnections, interdependencies	Limits	Resilience	Holistic	Science	Score
Indicators										
Well-being Index	Social indicator, Analytical	Similar to the barometer of sustainability and is based on the concept that a healthy environment is a requirement for healthy humans	No - Multiple agents but single system	No	No	No	No	No	Yes	**1**
Sustainability Performance Index	Environmental indicator, Analytical	Is an input oriented indicator that gauges environmental sustainability allowing comparison among nations - calculates the area required for a process to be completely embedded into the biosphere	No - Multiple agents but single system	No	No	No	No	No, tries to integrate though only process wise	Yes	**1**
Living Planet Index	Ecological Indicator, Analytical	Measure of the state of natural ecosystems according to the abundance of animal species they support	No - Multiple agents but single system	No	No	No	No	No	Yes	**1**
Product Sustainability Index	Product, Analytical	Is based on exergy calculations hence is "the fraction of the area per inhabitant related to the delivery of a certain product or service unit". The PSI consists of aggregate of environmental, social and economic indicators	Yes	No	No	No	No	Integrates the three systems but is still reductionist	Yes	**2**
Environmental Sustainability Index	Indicator, criteria based, Analytical	integrated tool that serves to identify key issues in society and national level environmental programs	No - Multiple agents but single system	No	No	No	No	Integrates the three systems but is still reductionist	Yes	**1**
Genuine Progress Indicator	Economic + Social indicator, Analytical	an adjusted Gross Domestic Product (GDP) which now reflects the well-being of the people - aimed at reflecting the state of the economy more accurately	No - Multiple agents but single system	No	No	No	No	No	Yes	**1**
Genuine Savings Indicator	Economic + Social indicator, Analytical	is essentially an accounting framework which includes welfare measures that account for resources, their discovery as well as environmental impacts where negative savings indicate unsustainability	No - Multiple agents but single system	No	No	No	No	No	Yes	**1**
Human Development Index	Social indicator, Analytical	Is a social indicator based on life expectancy, adult literacy together with years of education (primary, secondary and tertiary enrolment) and GDP per capita expressed in monetary terms.	No - Multiple agents but single system	No	No	No	No	No	Yes	**1**
Sustainable Process Index	Principle based, Analytical	Compares human mass and energy flows with natural flows and thus measures the measures the ecological impact of a process	No - Multiple agents but single system	No	Yes	No	No	No	Yes	**2**

Indicator	Type of tool	Description/purpose	Multiple Agents/systems	Dynamics	Interconnections, interdependencies	Limits	Resilience	Holistic	Science	Score
Carbon Footprint	Analytical	GHG emission calculation for organisations, product, event, etc.	No	No	No	No	No	No	Yes	**1**
Dow Jones Sustainability Index	Economical, Analytical	Is used to identify and track the performance of sustainably run companies.	No	No	No	No	No	No	No	**0**
Tools for sustainability										
Life Cycle Assessment	Environmental, Analytical	Analytical tool to determine environmental impact of products and services along their life cycles	No - Multiple agents but single system	No	Yes	No, but proposes hotspots	No	Mainly reductionist but depends on scope	Yes	**2**
Life Cycle Costing	Economic, Analytical	is an economic analytical tool used to determine “total costs of a product, process or activity discounted over its lifetime”	No - Multiple agents but single system	No	No, only considers the economic system	No	No	Mainly reductionist but depends on scope	Economic theory	**0**
Social Life Cycle Assessment	Social, Analytical	Tool to determine social impact of products and services along their life cycles	No - Multiple agents but single system	No	No, only considers the social system	No	No	Mainly reductionist but depends on scope	No	**0**
Risk Analysis	Procedural and Analytical	Risk assessment is the process of estimating the likelihood and magnitude of the occurrence of an unwanted, adverse effect.	Yes, depends on scope	Yes	Yes	Yes	Yes	Can be holistic depending on scope	Yes	**6**
Critical Limits and Critical Natural Capital	Principle based, analytical	A sustainability assessment approach based on Ecological Economics - natural substitutability vs. technology.	No	No	No	No	No	No, lacks social	Yes	**1**
Cost Benefit Analysis	Analytical	A tool that monetises costs and benefits so as to choose the best choice from a given number of choices.	No	No	No	No	No	No	No	**0**
Multi-Criteria analysis	Analytical	A decision making method to decide on the best choice out of a given number of choices.	No	No	No	No	No	No	No	**0**

Firstly, all of the assessments methods work well for their designed purposes. It was also found that most of the assessments are based on taking a snapshot in time for the assessment. Nearly all indicator based assessments analyse multiple agents of a single system. However, they fail to take the future into account and rarely take system dynamics into account. A significant drawback of most assessment methods is that they attempt to use local/regional data but are unable to differentiate the results in terms of spatial locality.

All indicator based assessments lack holism as they measure one or a handful of dimensions relevant to sustainability and do not attempt to see the whole system beyond its parts even when there is some integration of different systems. Integrated methods fared slightly better than the indicator based methods with respect to assessing multiple agents and multiples systems in the assessment. However, most assessment methods still failed to take interconnections and interdependencies of the different agents and systems into account. Due to these failures, most could not be considered holistic.

With respect to dynamics, system limits and resilience, it was found that some of the methods that took system dynamics into account were also able to provide indication of system limits (e.g. ecosystem resilience). However, very few assessment methods considered the possibility of limits in the assessment. The ones that were able to determine some limits, for example Ecological Footprint, did so only in terms of a single dimension such as land. Another criterion which is lacking in existing methods and models is resilience. However, two methods, ecological resilience and risk assessment, were found to be able to provide indication of resilience and these two methods also scored the highest in terms of the number of criteria they were able to assess. The highest score came from the "tools of sustainability" category where risk assessment was able to take most of the criteria into account. Table 6 shows the methods and models that scored high with respect to the criteria contained within them. Since most of the methods only took one of the criteria into account, all methods that scored greater than 1 will be examined in the following chapter.

Table 6: Candidates for new model

Method/model	Score/7
Risk Assessment	6
Ecosystem Resilience	4
Sustainable Process Index	2
Life Cycle Assessment	2
Product sustainability index	2
Ecological Footprint	2
Barometer for sustainability	2
Sustainability assessment by fuzzy evaluation (SAFE)	2

Risk assessment scored high for its potential as a rigorous assessment based on its ability to change scope of the assessment. With a broad scope, the assessment can cover almost all the criteria needed to assess complex system sustainability as it is basically an analytical tool and can be applicable to determine risk. Attributes of risk assessment with respect to sustainability and complex systems are discussed in the following chapter. Ecosystem Resilience has a high score as it incorporates most of the features required to assess sustainability of complex systems. It, like risk assessment, is depended on the scope of assessment and what is being assessed. However, there are some major drawbacks with this indicator apart from its focus as an environmental assessment tool and may not be a suitable measure of resilience due to the methodology used. However, this indicator, together with the others given in the table, is reviewed in chapter 4 as they show much potential with respect to some of the significant criteria for assessing sustainability of complex systems.

3.3 CHAPTER CONCLUSIONS

This chapter introduces seven criteria with which to assess existing assessment methods and models to determine whether they can be used to assess sustainability of complex systems. The criteria pertaining to multiple agents/systems; dynamics; interconnections and interdependencies; limits; resilience; holistic nature; and science show that most of the existing methods and model are unsuitable for tackling complex systems hence do not assess true sustainability. While most include some of the criteria to assess sustainability of complex systems, they do not incorporate enough of the necessary criteria thus failing at being holistic.

The analysis of existing models and methods for sustainability assessment highlighted a number of potential methods and models that may be beneficial if integrated as a new model. Eight existing methods and models, all of which have at least two of the seven criteria necessary for assessment of complex system sustainability, are chosen for further analysis. These tools include Risk Assessment (analytical tool); Ecosystem Resilience (integrated method); Sustainable Process Index (an indicator); Life Cycle Assessment (analytical tool); Product sustainability index (an indicator); Ecological Footprint (integrated method); Barometer for sustainability (integrated method); and Sustainability assessment by fuzzy evaluation (SAFE) (integrated method) and may hold the key in assessing sustainability of complex systems. These are examine and analysed further in Chapter 4.

CHAPTER 4: CHOICE OF METHODS FOR INTEGRATION

The previous chapter evaluated existing models and methods to determine if they are able to assess sustainability of complex systems. The evaluation was carried out using a set of criteria derived from behaviour of complex systems where it was deemed that a sustainability assessment method or model should have the ability to:

1. Take complexity of the system into account by:
    a. Recognising the existence of multiple agents and system levels;
    b. Recognising interconnections and interdependencies;
    c. Taking system dynamics into account (time and space);
    d. Recognising system limits or thresholds;
    e. Recognising resilience and adaptive capacity; and
    f. Being holistic; and
2. Be based on science where appropriate.

The evaluation of existing methods and models showed that none of the assessments contained all of the criteria required for assessing complex systems. However, the results of the evaluation presented eight models and methods which were able to take some characteristics of complex systems into account. These include:

- Risk Assessment;
- Ecosystem Resilience;
- Sustainable Process Index;
- Life Cycle Assessment;
- Product sustainability index;
- Ecological Footprint;
- Barometer for sustainability; and
- Sustainability assessment by fuzzy evaluation (SAFE).

All of the models given above have their own advantages and disadvantages with respect to providing information required for sustainability. However, there are too many to be integrated together unless the integration is in the form of a tool box of assessment methods. The purpose of this research is to pick the most promising of the existing assessment methods and models and integrate them to build a new model for assessing sustainability of complex systems. Thus the 8 methods above are analysed further with the aim of discovering which ones would be better suited for integration. This chapter focuses on the advantages and disadvantages of the eight models revisited from Chapter 3 resulting in two methods being chosen for integration. Chapter 5 then discusses the possible ways of carrying out the integration with respect to existing integrations as well as presenting the new model.

4.1 METHOD COMPARISON AND SELECTION

Selection of methods for integration can depend on a number of factors including the need for integration, ease of integration, availability of data and support as well as practitioner knowledge. Generally, all of these tools may be integrated together and some of these tools may be extended, in terms of their boundaries and scope, to enable them to include characteristics of complex systems that are just beyond their reach. For example, LCA may be extended to allow for the social and economic dimensions to be analysed thus improving its abilities in terms of becoming a more holistic tool. Choosing the most appropriate methods for integrating will be based on a number of factors such as whether:

- The assessment methods have been standardised;
- Readily availability of literature as guides;
- It is used for education, planning and policy development;
- Databases for the methods exist;
- Research with respect to the assessment method has to its own academic journal (i.e. indicating whether there is high volume of research in progress);
- The assessment methods and their results are widely communicated and accepted;
- The assessment method comprises of the necessary characteristics to be integrated with RA (i.e. if there have been previous attempts to integrate); and
- The assessment method complements each other.

4.1.1 RISK ASSESSMENT

Risk assessment (RA) scored the highest in terms of its ability to relate to the characteristics of complex systems. In addition, RA can provide the following benefits:

- If extended, RA is able to assess risk pertaining to different temporal and spatial scales and hence may be useful for keeping track of the system dynamics;

- RA can be holistic if the boundaries and scope of the assessment are broadened to incorporate the systems that need to be assessed;
- RA is one of the oldest methods available to the scientific community and is well known to those in management, governance and engineering; thus, communication of the results should be relatively easy;
- There is on-going research in the field which can lead to improvement in techniques, development of databases, etc.;
- There are many databases for calculating risk and the problem lies in finding the suitable database for the assessment;
- RA is widely used by many people ranging from government, business and academia; and
- RA is now standardised by the International Standards Organisation (ISO/IEC 31010:2009).

Further to the above, the results of RA may provide information directly related to unsustainability. This will be discussed further in Chapter 7. The above, together with RA's ability to account for most of the characteristics of complex systems makes it the first choice as a tool for integration.

4.1.2 ECOLOGICAL RESILIENCE

Ecosystem Resilience scored the second highest with its promising ability to taking into account characteristics such as interconnectedness, interdependencies, systems limits and resilience. It is an indicator that is meant to measure the resilience of ecosystems. However, there is no internationally agreed method to measure ecosystem resilience. The best that exists is a range of environmental indicators used to measure maintenance or depletion of ecological resources as proxy. Keeping track of the indicators may act as a gauge, indicating the health of ecosystems over time. Resilience varies from system to system and thus different environmental indicators can be used. These indicators are already in use by other assessment methods such as Ecological Footprint and LCA. Since there is no acceptable method for measuring ecosystem resilience, this method is not considered to be an appropriate method for integration.

4.1.3 ECOLOGICAL FOOTPRINT

As mentioned in Chapter 2, Ecological Footprint is based on measuring carrying capacity in terms of the amount of land required to support a defined population (Rees, 1992; Rees and Wackernagel, 1994). While the concept of carrying capacity comes very close to being a measure of limits, the result is only in terms of land, and significant system elements such as pollution in the environment are not included. In terms of the calculations, the Ecological Footprint is best suited for raising awareness and educating the masses regarding production and consumption patterns. Ecological Footprint is widely used by scientists, businesses, governments, agencies, individuals, and institutions. However, according to some (Barrett et al. 2004; McManus and Haughton 2006; Collins and Flynn, 2007; Graymore et al. 2008; Wilson and Grant, 2009) the calculation of Ecological Footprint is not sophisticated enough for informing community planning and policy development, especially at the regional level.

In terms of literature, there are numerous books on the Ecological Footprint such as Wackernagel and Rees (1996). The Ecological Footprint also has its own standards produced by the Global Footprint Network (Global Footprint Network, 2009) in an attempt to provide guidance with the calculations. However, standardization has been criticized for compromising the “indicator's usefulness for administrative/political guidance, due to the methodology's lack of transparency and inability to identify local variations” (Aall and Norland, 2005). There is no specific scientific journal associated with the Ecological Footprint however there are many research articles published in ecology-related journals such as Ecological Economics which are able to provide guidance.

4.1.4 SUSTAINABLE PROCESS INDEX (SPI)

As mentioned in Chapter 2, SPI calculates the area required to embed a process into the ecosphere in a sustainable manner. SPI is thus based on the Ecological Footprint concept, resulting in an indicator based on area. SPI is much like LCA with respect to its ability to take upstream and downstream pressures into account (Krotscheck and Narodoslawsky, 1996) SPI is ISO 14000 compatible (Gwehenberger and Narodoslawsky, 2007) though it does not have a set of standards for itself. SPIonExcel, an Excel based software program is available for calculations (Sandholzer and Narodoslawsky, 2007) where data can be determined and compiled at the early stages of process development. With respect to use as a policy tool, SPI would suffer from similar shortfalls as the Ecological Footprint though the lifecycle aspect can be useful for the audience of the tool who are mainly engineers.

4.1.5 PRODUCT SUSTAINABILITY INDEX (PSI)

PSI, developed by Ford of Europe is a tool for sustainability management. It, like the SPI, is based on life cycle concepts such that impacts of the product's lifecycle are taken into account (Schmidt and Taylor, 2006) though they seem to neglect service and recycling stages (Schmidt et al., 2004), concentrating only on concerns that are eligible for engineers during the design process. PSI also uses concepts behind Life Cycle Costing to include economic and environmental systems in the calculations. The data are gathered from in-house and supplementary data are available in LCA databases. While PSI does not have standards of its own, it utilizes LCA standards (Schmidt, 2008) and has a spreadsheet based LCA application that is transparent and easy to track.

4.1.6 LIFE CYCLE ASSESSMENT (LCA)

LCA is a comprehensive analytical tool that is capable of investigating and analysing the ecological, and in some cases human health impacts, of inputs and outputs during the lifecycle of a product, process or service. There are two primary uses of LCA according to the literature: 1. The identification of hotspots during the lifecycle of a product, process or service and hence where the greatest improvements can be made; and 2. For comparing alternative products, processes or services (Tukker, 2000). Recently, LCA is also used for Environmental Product Declarations (Marin and Tobler, 2003). Increased awareness and understanding of LCA led to an accepted framework, international standards (ISO, 2006a and ISO, 2006b), guidelines, inventory methodology as well as text books on the subject (ISO, 1997; Guinée, 2002; Wenzel et al., 1997; Baumann and Tillman, 2004; Heijungs et al., 2009).

LCA's strengths are in accordance to its ability to quantify environmental burdens systematically where assessment is carried out across the entire life cycle. It is this ability to focus on the whole lifecycle perspective that makes LCA unique among other models as it helps to prevent shifting of problems from one stage of the lifecycle to another (Finnveden, 2009). LCA is data intensive and there are numerous databases available for use (Ecoinvent, US Input-Output database, Japanese Input-Output database, etc.). Furthermore, there is ongoing work on developing and improving the quality of databases per region (e.g. China, Australia) and possibly per industry.

4.1.7 BAROMETER OF SUSTAINABILITY

Barometer of Sustainability is an aggregated indicator with advantages stemming from its systems perspective. It is not widely used and has not been standardised. The research focus on the method is limited and there are only a few literature sources such as those by Prescott-Allen (2001) and Guijt and Moiseev (2001). The barometer presents a number of sub-indices and each of these require data for calculation. The Barometer of Sustainability comprises of the Well-being Index and as such part of the results is able to aid in policy development even though the method itself has not been taken centre stage like some of the other methods.

4.1.8 SUSTAINABILITY ASSESSMENT BY FUZZY EVALUATION (SAFE)

SAFE is “a scientific tool that permits simulatation of the dynamics of a system without a detailed mathematical description” *(*Phillis and Andriantiatsaholiniaina, 2001). It uses fuzzy logic reasoning as well as basic indicators to determine environmental integrity, economic efficiency and social welfare (Andriantiatsaholiniaina et al., 2004) and follows a similar method as that of the barometer of sustainability to determine human and ecological sustainability which contributes toward the overall sustainability indicator. There is some literature on the technique in terms of a book and numerous research articles (e.g. Phillis and Kouikoglou, 2009); however, the level of ongoing research in the area is not as prolific as other methods discussed here. Furthermore, there are no standards for the method or a specific journal both of which probably indicates the method’s infancy and current lack of acceptance by a broader audience.

Since the method makes use of existing indicators, data on these indicators are required and can be obtained from a number of sources such as the UN organizations, World Bank, etc. There is no existing database specifically for the method. The method is not widely used though there are a number of recent case studies in industry such Phillis and Davis (2009) assessing corporate sustainability, Musee and Lorenzen (2007) assessing gold mining in Australasia. There have been few attempts (Liu, 2007; Liu and Yu, 2009) at integrating it with other methods thus allowing for future research in the area. According to Phillis and Andriantiatsaholiniaina (2001), the method can be used for policymaking where the policymakers are able to choose the indicators to be included in the assessment. Table 7 summarises the above in terms of acceptance and proliferation of each method, potential for use in policy developments, availability of standards, literature, databases as well as whether the method has spawned its own field of research with its own journal, has been integrated with other methods, and can be communicated to a broader audience. All of these can indicate the level of acceptance in the scientific community.

Table 7: Summary of advantages, disadvantages and potential for assessing sustainability of complex systems among 8 existing methods and models

Method	Acceptance	Policy developments	Standards	Literature	Databases	Journal	Communication	Integrated	Score
Risk Assessment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8/8
Ecosystem Resilience	Theoretical	No	No	Yes	No	No	No	No	1/8
Sustainable Process Index	Yes, but not as much as LCA or EF	Yes	No	Yes	Yes	No	Yes - engineers	No	5/8
Life Cycle Assessment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8/8
Product Sustainability Index	Yes, but not as much as LCA	Yes	No	Yes	Yes	No	Yes- engineers	No	5/8
Ecological Footprint	Yes	No	Yes	Yes	Yes	No	Yes	Yes	6/8
Barometer of Sustainability	No	Yes	No	Yes	Yes	No	Yes	Yes	5/8
Sustainability assessment by fuzzy evaluation (SAFE)	No	Yes	No	Yes	No	No	Yes	No	3/8

The results of this comparison show that RA and LCA scored the highest and together with their respective abilities to account for some of the characteristics of complex systems, they are the favoured methods for integration for this research.

4.2 LCA AND RA FOR ASSESSING SUSTAINABILITY OF COMPLEX SYSTEMS

LCA and RA are not new methods in the scientific community and as such they have branched out into various fields of research and is used by policymakers, researchers, businesses, governments, etc. In terms of assessing complex systems, they both have attributes that may be capitalized upon where the shortfalls of one method may be overcome by the other. While there are countless papers on LCA, sustainability and risk assessment individually, the three concepts have been treated separately where risk assessment is seen more as a policy tool than a means to assess sustainability. Sustainability is closely associated with risk (Krysiak, 2009) in that should risks that can disrupt an activity be minimized or eliminated, the task may be continued. For the activity to continue sustainably, it should not degrade the system in which it functions, operating within limits that would not risk the wellbeing of the agents, interconnections and interdependencies and thus the wellbeing of the system.

As discussed previously, LCA is a tool for assessing environmental impacts. It is one dimensional or in terms of complex systems, it only deals with a single system – the environment. The environmental dimension for which it was designed takes precedence thus LCA is not holistic. However, the other two systems, the social and economic, may be incorporated through integrating LCA with social LCA (SLCA) and Life Cycle Costing (LCC). The potential for integrated LCA-SLCA-LCC for sustainability assessment have been discussed (Kloepffer, 2008) though due to SLCA's infancy, there has been little progress. The main point is that LCA's advantages, coupled with the proliferation of its use for multiple and various purposes, means that it is well developed and has the backing of the scientific community. This is advantageous in further development of the method and continued use, development of databases for more data, more research into finding solutions for the weaknesses, etc. and hence has potential for assessing sustainability via an integrated model.

The greatest strength of LCA for complex systems is that the inventory takes into account all inputs and outputs which, if given broad boundaries, can encompass many of the interconnections and interdependencies between different systems if desired. The inventory phase is the most work intensive and time consuming compared to other phases in an LCA, mainly because of data collection. The data collection can be less time consuming if good databases are available and if customers and suppliers are willing to assist with information however this is restricted by confidentiality in some cases. Nevertheless, many LCA databases exist and can normally be purchased together with LCA software. Data on transport, extraction of raw materials, processing of materials, production of usually used products such as plastic and cardboard, and disposal can normally be found in an LCA database. For the overall LCA to be accurate and thus more product-specific, site-specific data are required. The data should include all inputs and outputs from the processes. Inputs are energy (renewable and non-renewable), water, raw materials, etc. Outputs are the products and co-products, and emission (CO_2, CH_4, SO_2, NO_x and CO) to air, water and soil (total suspended solids: TSS, biological oxygen demand: BOD, chemical oxygen demand: COD and chlorinated organic compounds: AOXs) and solid waste generation (municipal solid waste: MSW and landfills).

LCA is a highly regarded tool that can help quantify environmental impact or potential environmental impact of a product or process during its life cycle. The methodological framework has been standardized by SETAC and ISO, and numerous software products such as SimaPro, GaBi, etc. are available to assist in the process. Nevertheless, a number of techniques, methodology and communication limitations still exist, including data availability, existence of various impact assessment methodologies, lack of spatial resolution, inability to take time into account, etc. Many improvements to the technique have taken place over the years to reduce uncertainty and increase robustness. Standardization of the technique and the availability of industrial data in selected datasets have solved many of the issues discussed.

In terms of recent advances, integration of other techniques such as risk assessment and Life Cycle Costing for example, has been undertaken with certain degrees of success. From a sustainable development point of view, LCA can assist in providing data and indicators for environmental impacts. LCA is the only method that forms a comprehensive inventory of inputs and outputs of the system. It also forces a system boundary such that all relevant aspects of a system are catered to while identifying areas that are excluded. However, it remains an analytical and support tool and its use in direct decision making for sustainability is still evolving.

RA and risk management are routine aspects of life, carried out from personal, organizational, regional levels. The literature found on risk, RA and risk management is as yet dominated by the scientific uses such as in the pharmaceutical and health industries. While RA is also well established in the environmental sector, there is very little mention of its use as a potential tool for sustainable development. Most of the development in RA is concentrated around mitigating limitations related to uncertainty, communication etc. as is the case for LCA developments. In addition, the use of software tools to facilitate PRA is also under development. However, as mentioned previously, there is limited work in the use of risk and RA for sustainable development purposes despite RA being able to account for many characteristics of complex systems (time and space risks for system dynamics, help understand the connections between agents and how changes in one systems may affect another, take into account the future, enable a holistic view of the complex systems in which human beings function and thus identify means for reducing risks that may cause regime shifts or flips in system behaviour etc. to name a few). To a large extent, risk assessment and sustainable development both serve the same purpose: to assist continuation whilst minimizing adverse effects. The main gap in the research is concerned with the integration of a day-to-day technique such as RA with the bigger picture that is sustainable development.

In light of the above, Life Cycle Assessment and Risk Assessment seem to be the most appropriate tools for integration from the list of methods identified from the last chapter. Since both techniques have advantages in terms of accounting for complex system behaviour, and additionally are scientifically accepted and extensive in their use, they are chosen for integration. There have been some attempt to integrate the two methods though the purpose of integration has been different from the one pursued in this thesis. Thus notable works with respect to integration of the two methods, as well as the proposed integrated model are discussed in Chapter 5.

4.3 CHAPTER CONCLUSIONS

The previous chapter results in eight existing methods and tools which account for some characteristics of complex systems. This chapter evaluates risk assessment (RA), ecosystem resilience, Sustainable Process Index, Life Cycle Assessment (LCA), Product Sustainability Index, Ecological Footprint, Barometer of Sustainability and Sustainability Assessment by Fuzzy Evaluation (SAFE) further in order to select the most suitable methods to integrate. Generally, all of these tools may be integrated together. Some of these tools may be extended in terms of their boundaries and scope to enable them to include certain characteristics of complex systems that are just beyond their reach. For example, LCA may be extended to allow for the social and economic dimensions to be analysed thus improving its abilities in terms of becoming a more holistic tool. Choosing the most appropriate methods for integration was based on factors such as whether:

- The assessment methods have been standardised;
- Ready availability of literature as guides exist;
- It is used for education, planning and policy development;
- Databases for the methods exist;
- Research with respect to the assessment method has to its own academic journal (i.e. indicating whether there is high volume of research in progress);
- The assessment methods and their results are widely communicated and accepted;
- The assessment method comprises of the necessary characteristics to be integrated with RA (i.e. if there have been previous attempts to integrate); and
- The assessment methods complement each other.

The results of the evaluation showed that LCA and RA have many of the required characteristics and thus is appropriate for integration.

CHAPTER 5: A NEW MODEL FOR ASSESSING SUSTAINABILITY OF COMPLEX SYSTEMS

Chapter 3 showed that none of the existing methods and models available for sustainability assessment is able to assess sustainability of complex systems because they failed to account for some of the significant characteristics of complex systems and CAS. Chapter 4 examined and analysed the methods and models that were able to take some aspects of complex systems into account. This resulted in two potential methods that may be integrated to form a sustainability assessment method applicable for complex systems. This chapter of the thesis focuses on developing a new method using the methods that were picked from the previous chapter where the methodology for developing the model can be described as being opportunistic. This section of the chapter introduces integrated assessment (IA), recent work in the area pertaining to the integration of LCA and RA, and then discusses the integration proposed for this research.

5.1 INTEGRATED ASSESSMENTS FOR SUSTAINABILITY

In the past, integrated assessments (IA) have mainly been used for developing models (Risbey et al., 1996). They are still used for model building; however, the focus has shifted slightly to "where a set of assessment tools and methods is used in an iterative and participatory process of planning for sustainable development" (Rotmans et al., 2000, pp 815). The development of IA for sustainability can be divided into three broad categories according to the purpose and process of integration. In the first category, selected methods or certain components of methods are integrated in order to improve or extend a particular model of assessment. For example, assessment of social and economic systems can be integrated into LCA so as to eliminate LCA's limitations pertaining to the lack of the social and economic dimensions and thus improving LCA's capabilities (De Udo Haes, 2004). Likewise, ecological and health risk assessments are integrated to form Integrated RA (Munns et al., 2003; Suter II et al., 2003).

The second category develops new models with respect to specific needs and goals. This includes integration of methods to develop new ways (models) to assess sustainability. For example, a new method for sustainability assessment called Life Cycle Sustainability Analysis (LCSA) proposes to integrate Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA) and Life Cycle Assessment (LCA) so as to take the economic, social and environmental dimensions into account (Heijungs et al., 2009). Another example, Integrated Sustainability Assessment (ISA) which is defined by Weaver and Rotmans (2006, p291) as “a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development”, also falls into the second category. This strategy can also be labelled as “hybrid analysis” (Udo de Haes et al., 2004).

The third category of models can be described as “tool-box” strategies (Wrisberg et al. 2002). This is where tools (i.e. existing methods) that are complementary with each other are used “without attempts to bring the analysis into one formal structure” (De Udo Haes, 2004).

According to work by Eggenberger and Partidario (2000); Scrase and Sheate (2002); Dovers (2005); Weaver and Rotmans (2006); Gibson (2006), etc., there are many stages or dimensions at which integration can be carried out:

1. Integration of various sustainability concerns at the objective formation stage;
2. Integration of various values and principles for sustainability at the scoping stage;
3. Integration of methods: qualitative and quantitative;
4. “Integration of different ‘internally integrated’ sustainability assessments to form a coherent assessment regime in support of sustainability-oriented governance.” (Weaver and Rotmans, 2006); and
5. Integration and inclusion of stakeholders, policymakers, social learning, etc. such that a wide knowledge base with multiple sources of information is available for use during the process.

This research contributes to the integration of different sustainability assessments (Number 4 in the list above) by developing a model which integrates the most suitable methods resulting from the evaluation and analysis carried out before. RA and LCA are the main focus of the integration and, as mentioned briefly, there have already been discussion or attempts at integrating the two methods (Guin´ee and Heijungs, 1993; Assies, 1998; CHAINET, 1998; Cowell et al., 2002; Nishioka et al., 2002; Wrisberg et al*.* 2002; Sonnemann et al., 2004; Pant et al. 2004; Jolliet et al. 2006; Larsen and Hauschild; 2007Kikuchi and Hirao, 2009). Table 8 compares the three categories in terms of their purpose, advantages, disadvantages and how LCA and RA may be integrated in accordance to each category. Given that each method of integration has significant advantages and disadvantages, it is not possible to determine which one of the three is the best in general.

Table 8: Comparison of integration methods

	Method of integration		
	Extension	**Hybrid analysis**	**Tool-box**
Description	A chosen method is extended to eliminate limitations with respect to a specific goal	Different tools are connected seamlessly with each other via data flows.	Different tools are applied in parallel with each other to complement each other
Purpose	To reduce limitations of an existing method	Either to improve one method/model or to develop a new method/model	To use a variety of methods according to the goal of study
Advantages	The result is a detailed method with broader scope; Well defined, consistent framework used as starting point where the established method is tweaked to incorporate missing dimensions.	Established methods can provide a solid base for integration; A number of different tools may be integrated; Enables the interactive use of existing databases thus reducing the cost of analysis.	High flexibility; A wide variety of models can be used; Enables separate use of databases for each method.
Disadvantages	Not very flexible as the result is one consistent model; May create a super tool - data and time intensive; Conflict between the core method and the extension may result	Increased complexity as data flows need to be somewhat compatible; More rigid than the toolbox method in terms of data input	Different methods give different scales of results and integration of results requires weighting; different tools may have different and incompatible paradigms; Not widely used.
Example of how LCA and RA could be integrated	Either extend the current LCA or RA respectively by incorporating elements that extend their use as sustainability assessment methods	Internal integration of the two techniques via integrating of processes in each phase	Start with LCA and carry out RA; or start with RA and then do LCA
References	Udo de Haes et al., (2004)	Udo de Haes et al. (2004)	Udo de Haes et al. (2004); Wrisberg et al. (2002)

Human and Environmental Risk Assessment (HERA) is a project initiated in 1999 to assess risk to human health and the environment using household cleaning products as case studies. HERA is often associated with LCA and has since been developed into a methodology for assessing risk from chemical substances (HERA, 2005; Flemström et al., 2004; Bridges, 2003). In a comparison between HERA and LCA, Udo de Haes et al. (2006) outlines the similarities, differences and synergies with respect to:

- Level 1 - the basic equations used;
- Level 2 - Structure of the two models; and
- Level 3 - Application.

It is expected that the above levels apply to RA methods in general thus can indicate issues with LCA and RA integration models. According to the study, both HERA and LCA use the same fate and effect models; however, there are significant differences in model structure, specifically LCA's use of the functional unit. Other differences include "regional or life-cycle perspective, emission pulses or fluxes, scope of chemicals and types of impacts, use of characterization factors, spatial and temporal detail, aggregation of effects" (Udo de Haes et al., 2006). In terms of application, it was found that the two methods are complementary. One of the significant and relevant conclusions with respect to this study is as follows:

> "At Level 2, the level of the overall model structure, the two tools differ fundamentally on one point: the use of a functional unit in LCA in contrast to the use of processes in their full size in HERA. This goes together with the difference between a relative or an absolute approach, and a difference between an attribution and a full mode of analysis. This difference renders, at the level of the models underlying the tools as a whole, full integration of the two tools impossible. At level 3, the use of the two tools can be well combined in practice in the form of a toolbox."
>
> (Udo de Haes et al., 2006, pp 441)

Udo de Haes et al. (2006) is able to identify what constitutes as full integration based on their work on modes of analysis (Udo de Haes et al., 2000). Udo de Haes et al. (2000), separate analytical tools (those with a mathematical modelling component) into two modes: full mode; or attribution mode. In full mode of analysis, "processes are either included to their full extent, or they are excluded" (Udo de Haes et al., 2000; 48) where a process is defined as "an activity that takes place in the economy, converting substances, materials, products, and energy into other forms" (Udo de Haes et al., 2000; 48). In attribution mode, "one unit process provides the specified function, and all other unit processes contribute partially to that function" (Udo de Haes et al., 2000; 48). The two modes of analysis are shown in Figure 11. Since the goal of LCA is to investigate the function of the product rather than the product itself, LCA falls under the attribution mode category. Given that LCA falls under the attribution mode of analysis, integration of LCA and other methods may result in models that also fall under the attribution mode of analysis. This seems to be the key reason that Udo de Haes et al. (2006) do not consider the existing integration models mentioned as full integrations.

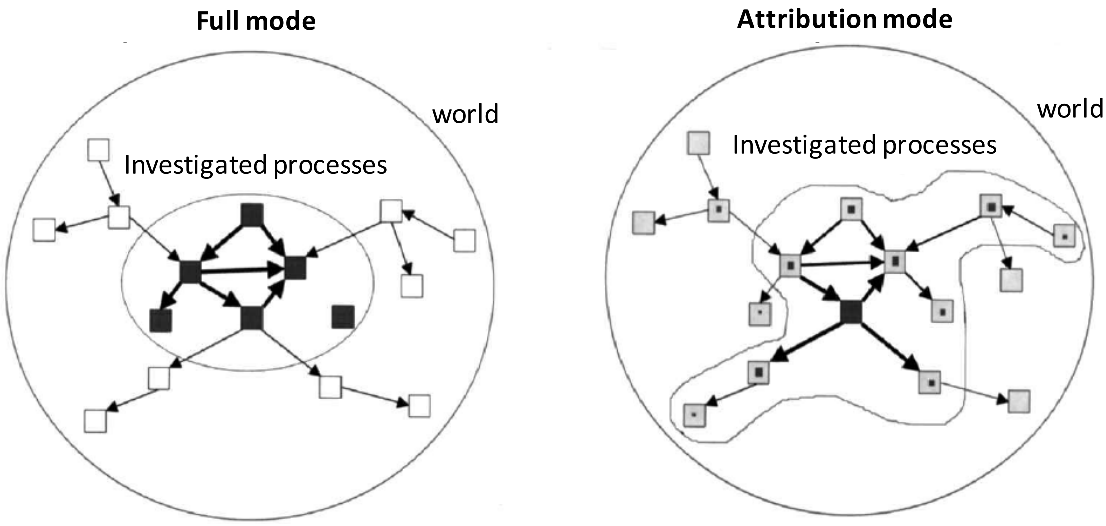

Figure 11: Full mode and attribution mode of analysis showing the unit processes investigated (Reproduced from Udo de Haes et al., 2000)

Wegener Sleeswijk et al. (2003) also share the view that the fundamental differences between RA and LCA make it impossible to integrate the two fully. However, they point out that integration is still possible. Therefore, numerous researchers have attempted to integrate LCA and RA (Nishioka et al., 2002; Matthews *et al*., 2002; Wegener Sleeswijk et al., 2003; Sonnemann et al., 2004; Pant et al., 2004; Wright et al., 2008; Kikuchi and Hirao, 2009). The seven studies are briefly reviewed to determine the method of integration; the purpose of the integration; the effectiveness of the integration; and whether the purpose of the integration is similar to the goal and context of this research.

5.2 EXISTING INTEGRATION OF LCA AND RA

The seven studies that are reviewed here include: 1. Nishioka et al. (2002); 2. Matthews et al. (2002); 3. Wegener Sleeswijk et al. (2003); 4. Sonnemann et al. (2004); 5. Pant et al. (2004); and 6. Wright et al. (2008); 7. Kikuchi and Hirao (2009). They are reviewed for three purposes:

1. To determine the extent to which integration has been carried out;
2. To determine how integration has been carried out; and
3. To identify the purpose of the integration (to determine whether they may be able to assess sustainability of complex systems).

5.2.1 METHOD OF INTEGRATION - NISHIOKA ET AL. (2002; 2006)

Nishioka et al. (2002 and 2006) consist of case studies where RA and LCA have been integrated to analyse net impact of insulation. The methodology given by Nishioka et al. (2002) consists of four phases as follows:

1. Determine how much energy would be saved in a 10-year period if all homes built during this period increased insulation levels from current practice to IECC 2000 levels.
2. Translating energy savings into emissions reductions given residential fuel types and fuels combusted by power plants affected by incremental changes in electricity consumption.
3. Estimating the influence of the air pollutants considered to affect human health at current ambient levels
4. Quantifying the health benefits of pollutant exposure reductions.

(Nishioka et al., 2002)

The authors state that each phase "involves developing a model that characterises the general trends, can be applied in a life cycle analysis, and can incorporate quantification of uncertainty" though the exact models themselves are not presented hence it is difficult to determine how LCA and RA has been integrated. According to Udo de Haes et al. (2006), the methodology used by the authors may be considered to be an extension of risk assessment rather than a full integration. The use of the functional unit has been disbanded which may provide the capacity for full mode analysis however this is not clear to see. In later studies, i.e. Nishioka et al. (2006), the authors incorporate concepts of RA into LCA in order to complete the LCA process by allowing the results to be presented as endpoints rather than presenting midpoints.

Overall, these studies reflect attempts at improving the Life Cycle Impact Assessment (LCIA) step, especially with respect to human toxicity which has been a barrier to complete LCA for some time. Since the framework for how RA and LCA are integrated is not given, it is difficult to determine where the integration faces issues. Nishioka et al. (2002) attempts to extend RA via incorporation of LCA concepts; and Nishioka et al. (2006) attempts to improve LCA via integrating RA.

5.2.2 METHOD OF INTEGRATION - MATTHEWS ET AL. (2002)

The integration of LCA and RA by Mathews et al. (2002) arises from: 1. The need to determine ways by which risk can be reduced at one point without transferring and increasing risk at another point; and 2. To ease the transformation of LCA's inventory into health impacts during the impact assessment step. Thus RA seeks guidance from LCA in order to translate risks into policy conclusions and LCA seeks guidance from RA to improve the impact assessment step. This study integrates Economic Input/ Output (EIO LCA) to RA. EIO LCA was developed to relate inputs of goods and services to outputs in an economy (Leontief, 1936). They propose a "process analysis" to LCA with the following steps:

1. Mass and energy balance outlining discharges to different mediums;
2. Translate discharges into ambient concentrations; and
3. Carry out conventional risk analysis to estimate human health effects.

The above would be a location-specific analysis rather than a general analysis and is an improvement on general LCA process which tends to give global impacts. This type of integration includes extending both LCA and RA to minimise their disadvantages.

5.2.3 METHOD OF INTEGRATION - WEGENER SLEESWIJK ET AL. (2003)

Wegener Sleeswijk et al. (2003) call for RA and LCA "to be incorporated in a common modelling tool, containing a common database" in the hope that "such an overall modelling tool would deliver both risks of individual chemicals and impact scores for all LCA impact categories as outputs" (Wegener Sleeswijk et al., 2003; p. 86). While they discuss the potential for integration, especially via removal of the functional unit concept as per Matthews et al. (2002) and Nishioka et al. (2002), they have not carried out the integration themselves.

5.2.4 METHOD OF INTEGRATION - SONNEMANN ET AL. (2004)

The integration by Sonnemann et al. (2004; chapter 6) is aimed at "spatial differentiation of life-cycles in order to facilitate a more integrated way of calculating environmental damage estimations in a chain perspective." This would help relate impact potentials to actual impacts and also allow the LCA results to be more consistent with RA. In the study, integration is carried out after the impact assessment step (Figure 12) where spatial scales determine whether conventional LCA or RA is used to calculate impact for global and local impacts respectively. The method is based on separating impact categories according to spatial scales – "it seems necessary to come to a spatial differentiation of life-cycles in order to facilitate a more integrated way of calculating environmental damage estimations in a chain perspective" (Sonnemann et al., 2004). The authors propose this differentiation to be based on chain length. Rather than investigating the product life cycle, they focus on estimating damage of industrial process chains related to the functional unit. They do this by considering a small number of processes and thus minimizing the number of sites (or impact locations) that need to be considered. This is based on their view that "only a small number of processes are responsible for the main part of the environmental impact" (Sonnemann et al., 2004).

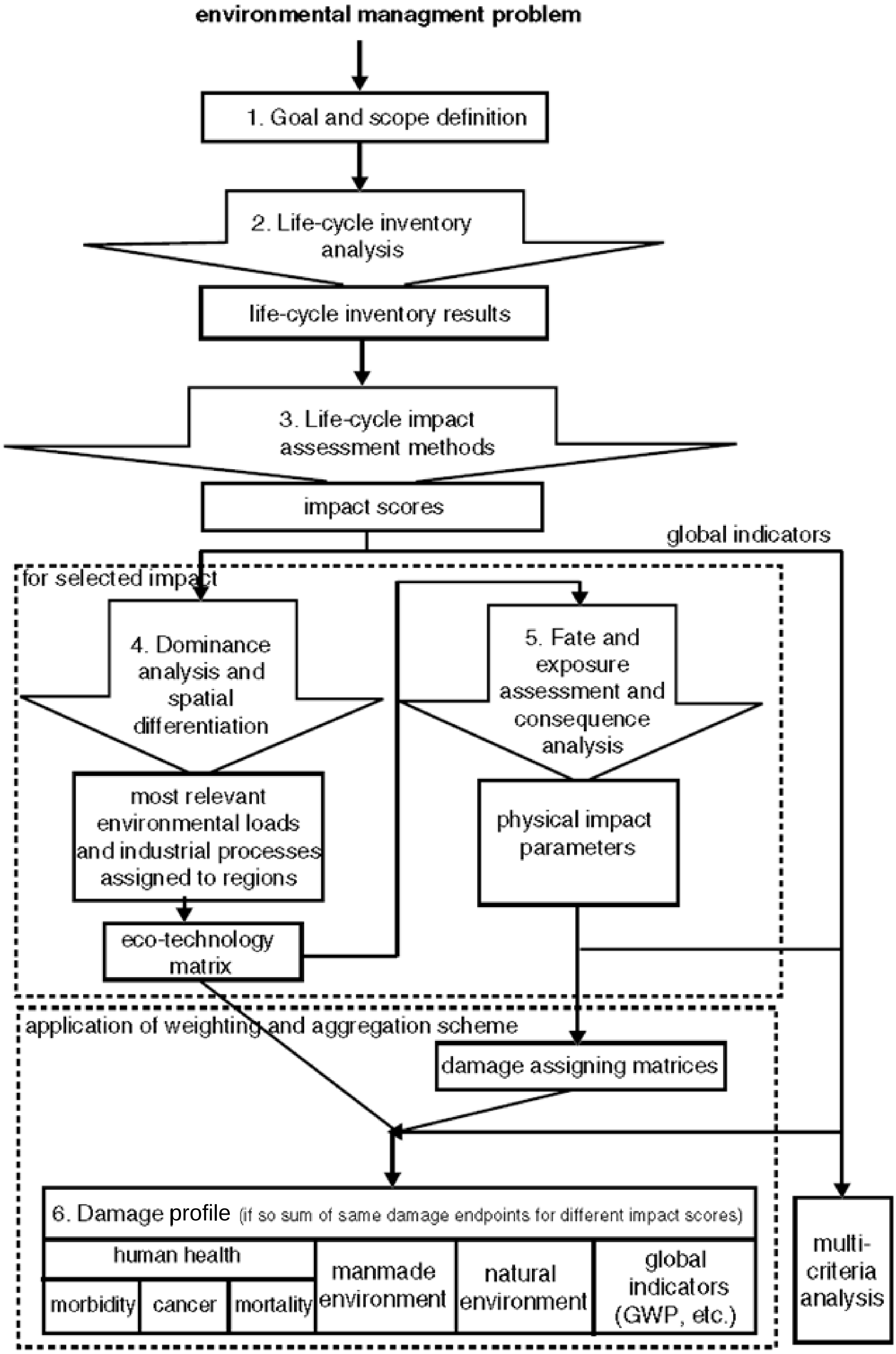

Figure 12: Integration of LCA and RA according to Sonnemann et al. (2004) – steps generating eco-technology and damage assigning phases

The method follows the conventional LCA framework but with additional steps after the impact assessment step. The most notable additional steps include:

- Dominance analysis and spatial differentiation which includes the following:
  - Dominance analysis for media;
  - Dominance analysis for processes and pollutants;
  - Spatial differentiation; and
- Generation of eco-technology and damage assigning matrices.

Dominance analysis is a means by which the assessment can focus on the most relevant impacts, media, processes and pollutants. It is basically a narrowing down of the impacts that are considered to be of highest significance together with their causes and location of impact. The process starts with the selection of an impact category deemed significant for further analysis. During dominance analyses for media, the emissions contributing to a particular impact category are segregated according to the types of media (air, water, land, etc.). These are presented graphically to aid the selection of the media for further investigation and analysis (Figure 13). Once the medium is decided upon, dominance analysis to determine the dominant processes and pollutants is performed where cut-off criteria are applied to determine a manageable number of dominant processes and pollutants for detailed assessment. The result of the dominance analysis is the identification of the most relevant processes as well as the respective pollutants.

The resulting processes and pollutants are then differentiated according to sites (origin), processes or regions (field of impact). The pollutants are assigned to the sites and/or regions according to the information available where site-specific or site-dependent assessments are carried out. The sites may be unknown and in that case, the impacts are considered to be global. The processes assigned to sites and regions, as well as the pollutants from the dominance analysis and spatial differentiation make up the eco-technology matrix. Fate and exposure assessment and consequence analysis steps of RA then follows resulting in the damage assigning matrix.

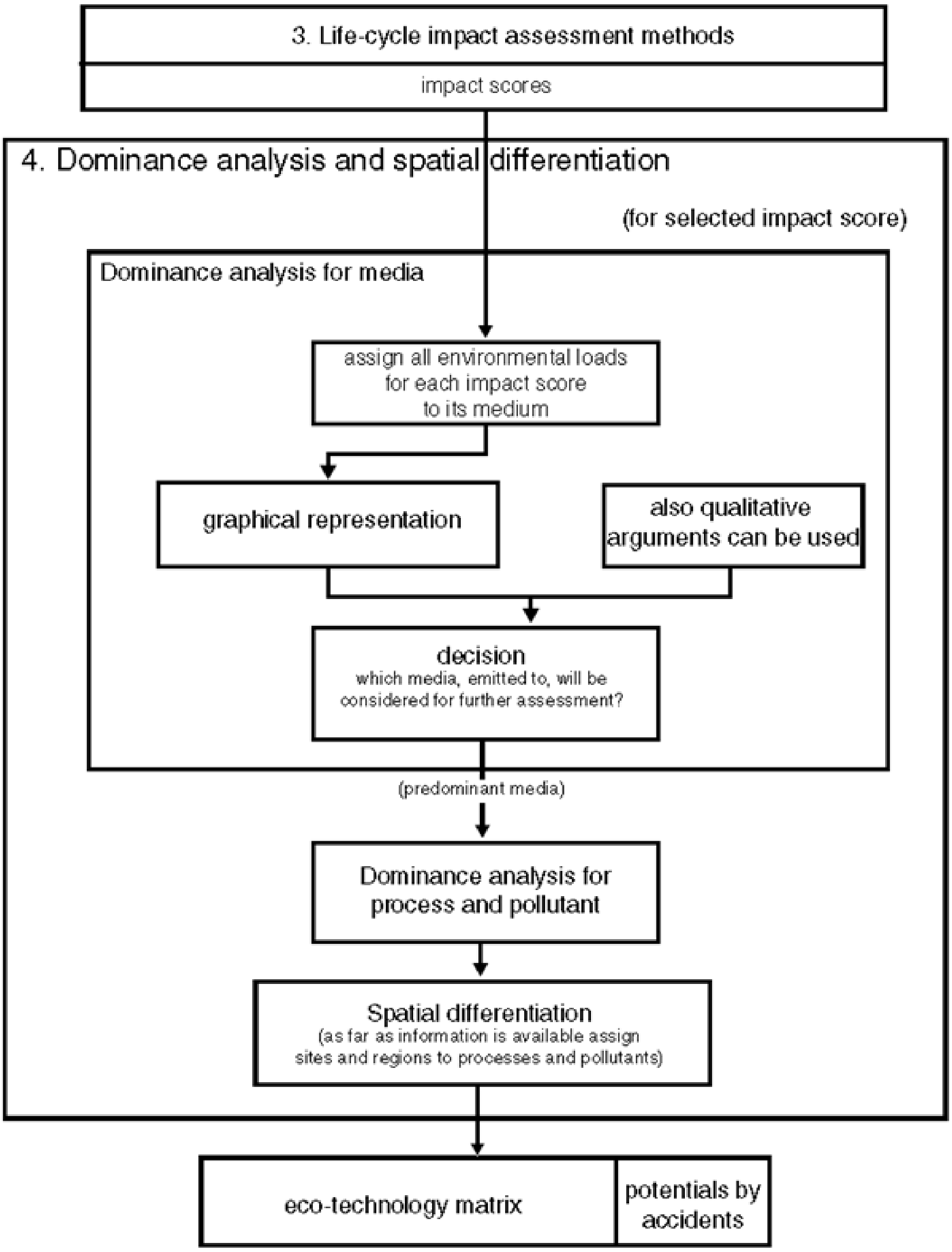

Figure 13: Dominance analysis and spatial differentiation (reproduced from Sonnemann et al. (2004))

Based on one of their case studies, Sonnemann et al. (2004) state that the study "clearly demonstrates the need for a more integrated approach that does not so easily allow two environmental impact analysis tools to provide such contradictory and inconsistent results", alluding to the idea that LCA and RA are in conflict with each other. This case study compared the impact of coal combustion in two scenarios. In the first scenario, the plant was located close to the mining area in a populated region. In the second scenario, the plant was located far from the mining region where the population was less dense. Their study showed contradictory results where LCA indicated lower impact for the first scenario due to minimised impact from transportation; and HERA, the RA method, indicated lower impact for the second scenario where fewer people were exposed to health concerns (Sonnemann et al., 2004; Udo de Haes et al., 2006). This indicates potential discrepancy because LCA gives priority to environmental impacts while RA gives priority to human health impacts. However, Udo de Haes et al. (2006, p441) argues that “only if two tools do produce independent, and thus possibly differing results, it is worthwhile to combine their use in a toolbox” though they have not explained the reason for this. Thus while the two methods can give contradictory results separately, their effectiveness as an integrated model has not been documented.

5.2.5 METHOD COMPARISON - PANT ET AL. (2004)

The study by Pant et al. (2004) analyses toxicological characterisation of chemicals in LCIA and RA with the aim of determining their domain of application. They carry out ERA and LCA by limiting the system boundaries such that they are nearly identical. In their case study on detergent, they only analyse the disposal stage, stating that it enables better comparison of the two methods. The concept of the functional unit is retained and is said to be LCIA and ERA compatible (Pant et al., 2004).

The study is not an integration of RA and LCA, but rather a comparison of methods consisting of a tiered approach to ERA based on local scale (using EU Eco-label method) and regional scale (The European System for Evaluating Substances (EUSES)), and LCIA using EDIP97 (chronic aquatic ecotoxicity), USES-LCA (Huijbregts et al., 2000) (freshwater aquatic ecotoxicity, marine water ecotoxicity) and IMPACT 2002 (aquatic ecotoxicity) separately. The impact categories of both ERA and LCA in this case study relate to ecotoxicity, an area for which more research has been called for by LCA practitioners (Finnveden, 2000; Crettaz et al. 2002; etc.). The results of this study suggests that limiting the scope of both LCA and RA to achieve compatibility of boundaries and scope would allow for common fate, exposure and effect results to be achieved.

5.2.6 METHOD OF INTEGRATION - WRIGHT ET AL. (2008)

The authors have combined an environmental fate and transport model (CHEMGL), EIO-LCA model and RA for the purpose of determining risks as a screening level analysis. The model developed by the authors is given in Figure 14. The aim of the case study was to identify the significant relative risks to humans and fish by comparing the relative risk of chemicals related to the life cycle of an emerging chemical of concern. The authors make use of the CHEMGL model to generate chemical concentrations for use in the RA tool. The RA tool is a spreadsheet developed by the authors for the purpose of calculating indicators in units of toluene equivalence as described by Guinée and Heijungs (1993) and results in the calculation of risk potentials. The EIO-LCA results in environmental releases from the selected stages of the life cycle. The relative risk is then calculated by multiplying the risk potential from the RA tool by environmental release from a combination of EIO-LCA results and literature based environmental release estimates.

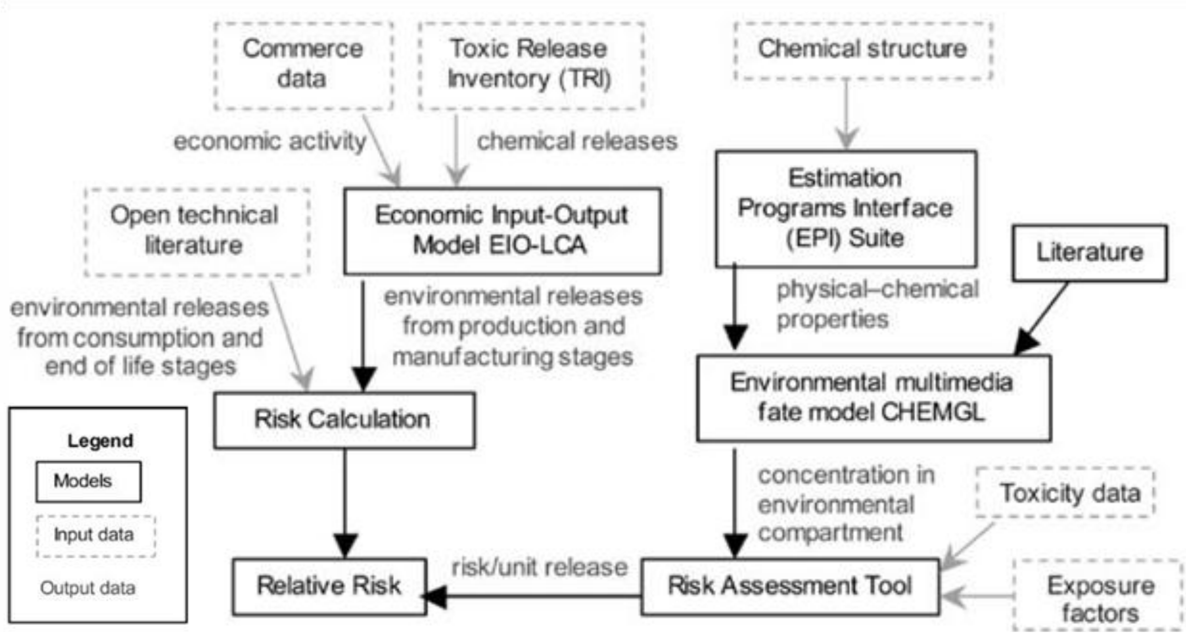

Figure 14: "Schematic illustration of the methodology used to integrate an environmental fate and transport model (CHEMGL), an economic input–output life cycle assessment (EIO-LCA) model, and a risk assessment tool for a screening-level analysis." (Reproduced from Wright et al., 2008)

The authors conclude that the integrated EIO-LCA with RA is suitable for screening level analysis where rapid LCIA is a necessity. However, while the use of EIO-LCA uses publicly available data based on an economic model and hence is inexpensive and appropriate for screening level analysis (Bilec et al. 2006), it suffers from some significant limitations with regard to trade-offs between process specificity and completeness of the system in terms of environmental effects (Hendrickson et al. 2006). This integration does not consider the concept of functional units and LCA is used to provide information for the calculation of risk potential for each stage of the life cycle and can be categorized as a hybrid analysis.

5.2.7 METHOD OF INTEGRATION - KIKUCHI AND HIRAO (2009)

According to the authors, local risks and life cycle environmental impact should be considered in order to supervise adverse effects (Kikuchi and Hirao, 2009). As such, they integrate LCA and RA for the purpose of aiding risk-based decision making. The model is aimed at onsite implementation by decision makers and stresses the need for systematic procedure in order to make sense of complicated and vast input of data the decision maker must consider. Their case study is based on “designing a metal cleaning process reducing chemical risks due to the use of a cleansing agent” (Kikuchi and Hirao, 2009; p945). The authors have developed the model using the type-zero method of integrated definition language (IDEF0) which is a useful tool for visualising activities and information flows, and is commonly used as a modelling approach for integration of assessment methods and tools (Ross 1985; Skander et al., 2008; Fukushima and Hirao, 2002; etc.)

The framework outlining the model integrating LCA and RA by Kikuchi and Hirao (2009) is given in Figure 15. Here two sets of inventory, one for LCA and the other for RA, are collected. The assessments are carried out separately and the potential impacts and risks resulting from each assessment are then interpreted. Since LCA and the plant-specific RA are carried out separately, i.e. elements of LCA and RA do not come into contact with each other than at the definition of the problem and the aggregation of the results, this study is essentially equivalent to a tool-box type of integration. Here LCA and RA may be carried out simultaneously or one after the other. Since the aggregated results are the sum of the results from an attribution mode of analysis (LCA) and a full mode of analysis (RA), the overall results may not be considered as a full integration and the integration is leaning towards a tool-box type of analysis.

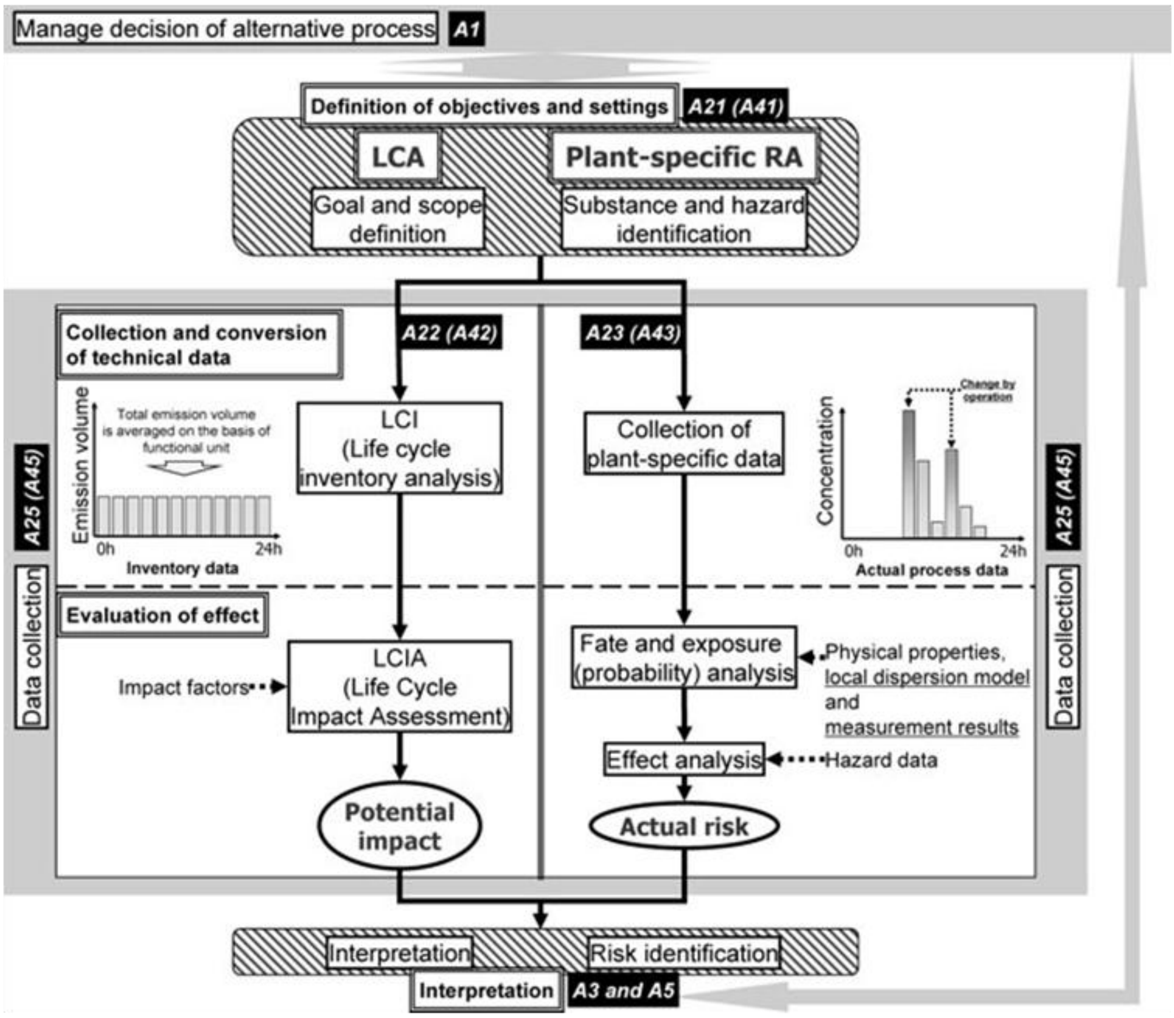

Figure 15: Integrated evaluation phases of life cycle assessment (LCA) and risk assessment (RA) with data requirements. The solid arrows represent procedures, the dotted arrows are data, and the required steps in each activity are represented by boxes. (Reproduced from Kikuchi and Hirao, 2009)

5.2.8 SYNOPSIS – INTEGRATIONS

The studies give indication that both RA and LCA have been utilised to improve each other's performance either by extension of LCA or RA respectively, or by incorporation of some significant aspect of one into the other. Integration of RA in order to help spatial differentiation is a common theme in the studies. RA is seen as a tool that can increase the effectiveness of LCA by allowing impacts to be analysed at the local or site specific level rather than considering all impacts as global. Table 9 summarises the purpose, method and outcome of integration. Note that integration for the purpose of assessing sustainability is not mentioned in any of these studies.

Table 9: Purpose, method and outcome of LCA + RA integration attempts

	Purpose of integration	Method of integration	Outcome of integration
Nishioka et al. (2002)	Integrate HERA and LCA	Eliminates the functional unit concept	Extension of RA
Matthews et al. (2002)	Improve LCA and improve RA	Eliminates the functional unit concept	Extension of both LCA and RA
Wegener Sleeswijk et al. (2003)	To determine risks and impacts	Eliminates the functional unit concept	Similar to Mathew et al and Nishioka et al
Sonnemann et al. (2004)	To make LCA more consistent with RA and to better relate impact potentials to actual impacts.	Integration at the LCIA step via the addition of dominance analysis and spatial differentiation. LCA feeds into RA and RA feeds into LCA	Inclusion of RA in LCA – essentially an extension of LCA
Pant et al. (2004)	Not integration but a comparison with similar system boundaries	Limits boundary of LCA to that of RA for comparative purposes	Comparison of LCA and RA
Wright et al. (2008)	Determine risk – screening level analysis	Combines economic input-output LCA, environmental fate and transport model and RA	Extension of RA where LCA is used to provide input regarding environmental releases.
Kikuchi and Hirao (2009)	Risk based decision making	Carries out plant specific RA and LCA systematically	Tool-box integration
Additional References	-	-	Udo de Haes et al., 2006

The review of the above studies leads to a number of conclusions and insights for integration of RA and LCA:

1. None of the integrations are aimed at providing a model for sustainability assessment. The respective purposes of the integrations is given in Table 9;
2. All of the integrations focus on human health risks or ecotoxicity risks quantitatively and do not take into account other types of risks (social);
3. The methodologies are all based on quantitative analysis with the exception of Sonnemann et al. (2004) where there were some areas where qualitative analysis was encouraged during dominance analysis and spatial differentiation;
4. None of the integrations can be considered as “full” integrations according to the distinction given by Udo de Haes et al. (2006);

a. While LCA only takes relevant unit processes into account (because it is an attribution mode analysis), HERA (type of RA) is capable of taking all processes into full account (Udo de Haes et al., 2006);

b. The barrier to full integration lies in LCA's use of the functional unit thus an integration that uses the concept of the functional unit is likely to be considered as an attribution method;

5. Some of the ways in which LCA and RA can be integrated are as follows:
    a. Separately conducting LCA and RA and integrating the results;
    b. Iterative use of LCA and RA where the results are either in terms of environmental impacts or in terms of risks;
    c. Incorporation of lifecycle thinking into the RA framework in order to better relate risk to policy;
    d. Incorporating risk into the LCA framework for spatial differentiation;
    e. Use of process chains rather than the use of all process units for a given functional unit and thus reducing scope and allowing more detailed assessment; and
    f. Limiting of system boundaries such that RA and LCA boundaries are identical.

5.3 NEW INTEGRATED MODEL

The second objective of the research is to develop a model to assess sustainability of complex systems. To this end, the advantages of the selected existing methods, LCA and RA, are to be capitalised. The model uses LCA for a number of purposes:

1. To develop a better understanding of the lifecycle of the product within the complex system;
2. To determine the inputs and outputs during the lifecycle stages of the product (as starting points for the RA in subsequent steps of the model); and
3. To highlight some of the significant impacts during the lifecycle (to allow for more investigation and RA of these stages).

Once some of the significant impacts during the lifecycle have been determined, the inputs and outputs related to those impacts are examined utilising RA. RA is used to identify risks from the particular inputs and outputs including temporal resolution to determine future risk. From the review of sustainability and assessments in Chapter 2 and Chapter 3, the use of a clearly outlined framework for carrying out the assessment seems to be in order. Thus the model will include all stages from goal and scope of assessment, to the interpretation and communication of results. The general framework for the resulting model is given in Figure 16. Each stage of the model, labelled A to G is described in further detail. The final chapter of this thesis contains some improvements upon this model.

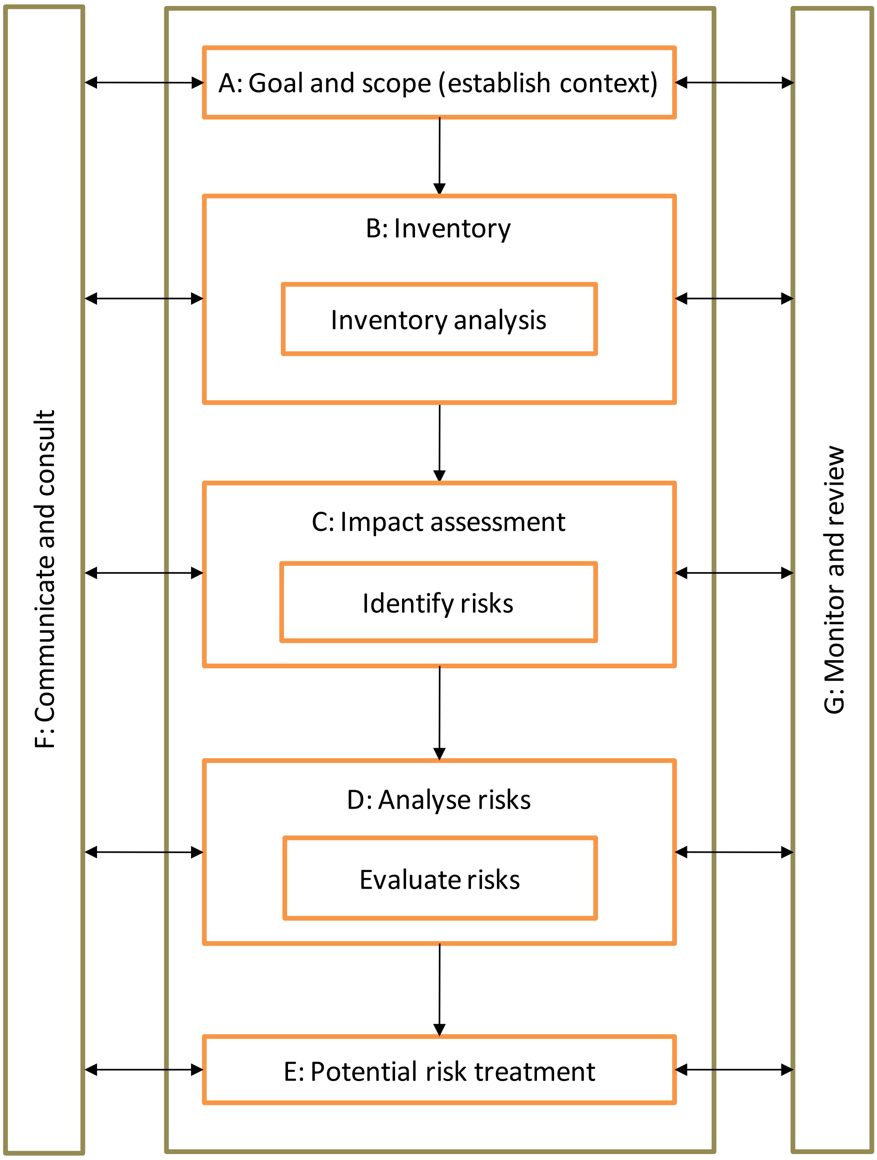

Figure 16: Sustainability assessment framework integrating LCA and RA

Since LCA and RA has been standardized, the standards (ISO 14040, ISO 14044, AS-NZS 4360-2004, ISO/IEC 31010:2009) together with handbooks (Guinée et al., 2002; Baumann and Tillman, 2004; etc.) can provide information and instruction on some of the elements to be addressed for parts of this model. The significant elements of the model are described as follows.

5.3.1 A: GOAL AND SCOPE

The first task of the model is to clearly establish the context and the goal, the reason for the study. Ideally, the goal of the assessment should be to assess sustainability of an activity (or product) within a complex system. Since this is the first step in planning for the assessment, a number of important attributes needs to be discussed in order to obtain a comprehensive assessment. Some of the elements include:

- The definition or description of the product/service, its function;
    - Outline of the product's/service's life cycle;
    - A functional unit as defined by ISO14040 and ISO 14044;
- Outline the scope of the study;
    - Intended audience;
    - System boundaries and allocation;
- Define the assessment procedures;
    - LCIA procedure and RA procedure;
- Data requirements and quality;
- Assumptions and any known limitations;
- Procedure to communicate results; and
- Peer review of study.

The above elements of the goal and scope stage for the model are described in more detail below.

DESCRIPTION OF THE PRODUCT/SERVICE

This is a standard procedure in most assessment methods where the object of assessment is described in terms of its background, purpose, function, etc. This helps define and communicate information about the product/service to other stakeholders while at the same time helping the practitioner obtain a better understanding of the product, the systems and sub-systems that need to be taken into account. The concept of the functional unit is uniquely related to LCA where products with similar functional units can be compared. The functional unit is defined as "quantified performance of a product system for use as a reference unit in a life cycle assessment study" (ISO, 2006a - Principles and Framework).

SCOPE OF THE STUDY

At this stage, the extent of the study can be defined with respect to the expectations of the practitioner and commissioner of the study. The audience of the results depends on the purpose of the study. For example, if the study is conducted for improvement of a product, then the audience can range from the Board of Directors of the company to the design team where higher level buy-in may be useful for changes to occur. The model is to be applied to a Small and Medium size Enterprise (SME). The simplest (reduced) version of the model is given in Figure 17. This is equivalent to a triple bottom line type model where the environment, social and economic systems have been reduced into three separate systems. A further reduction of the streamlined model in Figure 17 can be undertaken by concentrating on one type of system risk. However, this would defeat the purpose as the reductionist approach fails to account for the complexity by neglecting the interconnections and interdependencies with respect to the other systems.

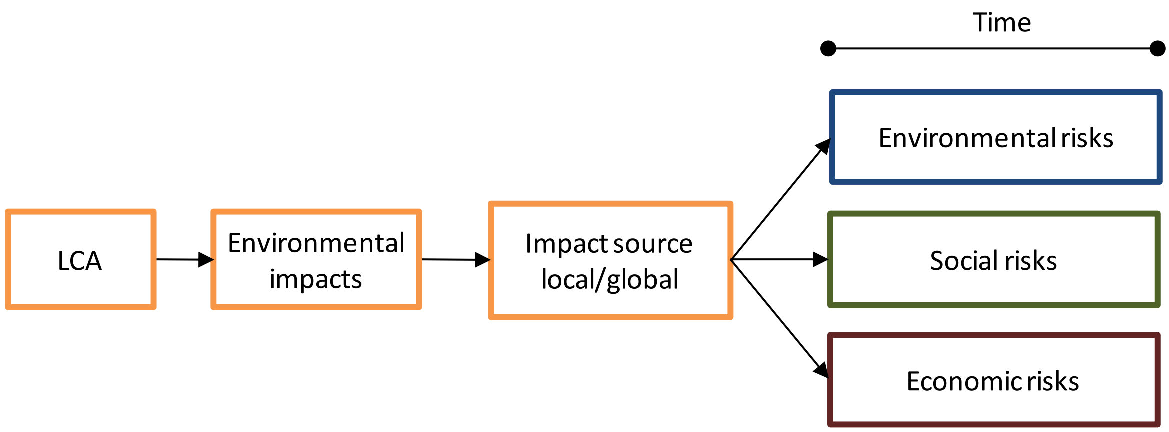

Figure 17: Streamlined sustainability assessment – reduced to three systems

While the model in Figure 17 may allow the identification of risk in different systems, it does not allow these risk events to be connected with the other systems. Often, a risk in one system propagates into another, but this model would not be able to make the appropriate connections across different system levels. This model can be modified according to the strong sustainability model (Brekke, 1997; Neumayer, 2003) as shown in Figure 18.

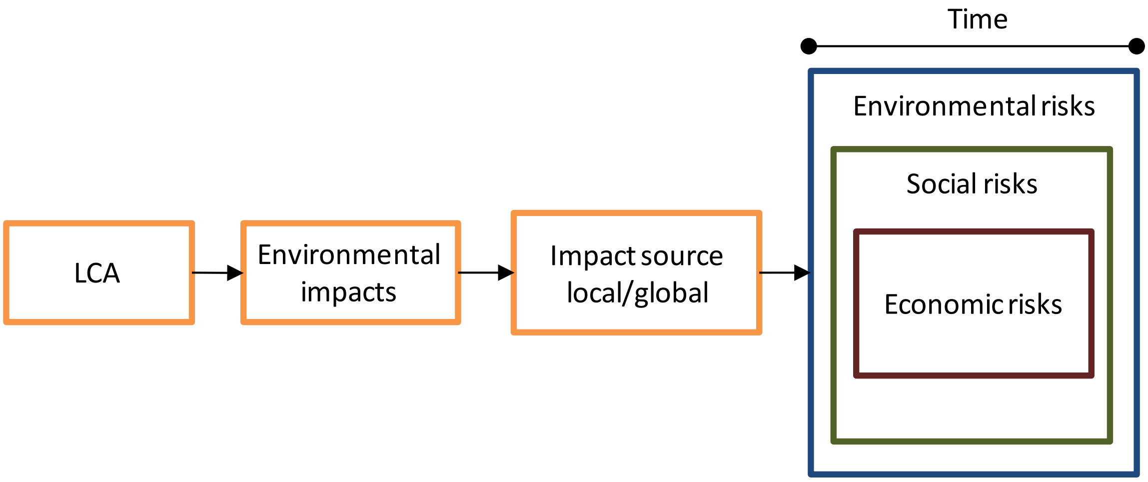

Figure 18: Streamlined sustainability assessment

Since the version of the model given in Figure 18 starts off with one set of data, i.e. environmental data for LCA, it is still a streamlined version. However, while this is still a streamlined version, it is able to trace the interconnections among the risks from the environmental, social and economic systems. In order to upgrade this model to a full holistic version, social and economic data are required as input. Figure 19 shows the pathways for full sustainability assessment. Data concerning the three systems are used to calculate impacts for each system with respect to spatial differentiation. This is done separately up until the RA stage where risks are identified and analyzed together with the interconnections. This model would entail the use of three separate databases, each similar to those required for the models in Figure 17 and Figure 18. While the assessment model in Figure 19 can accommodate most of the interconnections among the systems at the risk assessment stage, it still separates the three systems at the beginning thus remains to be reductionist to some extent.

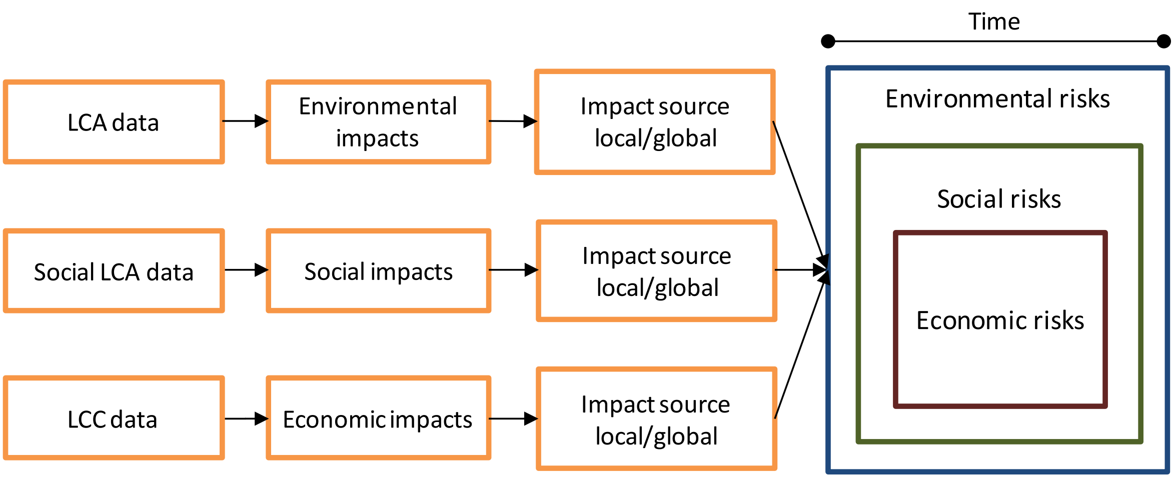

Figure 19: Full sustainability assessment comprised of streamlined assessments per system

A fully integrated sustainability assessment would require the interconnections at each step to be taken into account. I.e. the inputs and outputs of all the relevant data would be integrated into a single inventory; the connections among the different types of impact categories would be made via cause-effect chains together with the respective locations of the impacts; and subsequently, the resulting set of risks would also highlight the interconnections among the various systems together with time (Figure 20). Each box in the figure represents complex interactions. This is not the same as adding the assessment of the three systems separately as interaction of inputs and outputs would be at a deeper and holistic level where there is little or no segregation of systems. As with the reduced versions of the model, the practitioner is able to choose which systems will be included in the assessment as per the goal of the study. The choice of input data (inventory), the type of impacts (i.e. impact categories) and risks to assess (i.e. environmental, social or economic) depends upon the goal of assessment. The main difference between this model and the earlier ones is that this would be able to illustrate the interconnections more effectively and holistically.

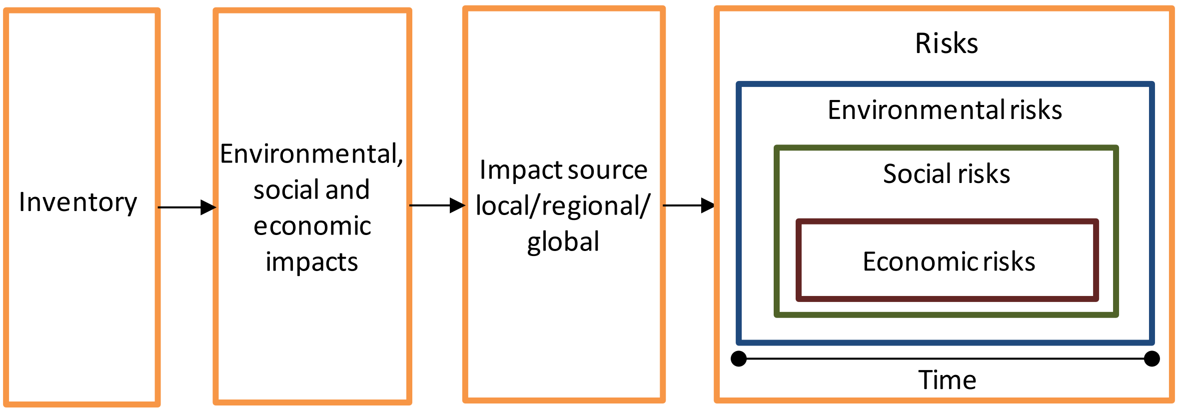

Figure 20: Complete sustainability assessment

SYSTEM BOUNDARIES

When introducing the concept of a complex system, the entire Earth system in which the activity or product is contained in, needs to be targeted. It means that impacts of the activity or product across different sub-systems or system levels needs to be analysed where risks across these sub-systems are analysed with respect to the impact to the overall Earth systems and subsequently the impact on social and human wellbeing. This is a considerable task, though a necessary one, in order to examine and understand the interactions, interconnections and overall complex behaviours that are an inherent part of complex systems. In order to simplify the above task, it is necessary to limit the scope of the study to the most significant aspects without compromising the ability to take complexity into account. The scope should include boundaries pertaining to time, space, dimensions, etc. Traditional LCA can be used to determine the most significant aspects in terms of environmental impacts. However, LCA lacks the ability to delve into the economic and social impacts due to the current limitations of the tool. It is likely that LCA would enable connections to systems other than the environmental system; however, these connections would not be clearly visible. A combination of LCA, SLCA and LCC data would be ideal because then the impact assessment would result in impacts across the three systems that are relevant to the assessment of sustainability thus allowing for the interconnections to be more apparent.

The normal scoping stage of LCA includes the definition of the functional unit. The functional unit is "a measure of the performance of the functional outputs of the product system" (ISO 14040: 2006) and it provides a reference which relates the inputs to the outputs of the product/service function. For products that provide a service, such as furniture products, defining an adequate functional unit may be challenging. ISO's LCA methodology and guidelines were developed from a product perspective. Thus it is unclear on how to define the functional unit of a service product. Nevertheless, the functional unit can be defined with respect to the primary function of the product (in this case seating) as well as the duration of product use and the expected characteristics of the user for whom the product was designed.

As mentioned earlier, LCA is an attribution mode analysis (De Haes et al., 2006) as it analyses the function of the product rather than the product itself. This means that the method includes one unit process in full and the other relevant processes only partially as it contributes to the function (Figure 11 shows the comparison between full and attribution modes of analysis). Unlike full mode analysis where processes are either included or excluded in full, the use of the functional unit means that one unit process will be included in full and the other relevant unit processes will be included partially as it applies to the function. This is likely to feed the debate on whether the integration is an attribution analysis or a full mode analysis. This model is an attribution mode analysis due to the use of LCA and the functional unit which are significant components of the model. In order to enable maximum coverage of the product and the related impacts, a full mode analysis may be beneficial though this would result in debate regarding which processes should be included or excluded in full. The functional unit concept is also a significant requirement for LCA comparison. While the goal of this study is not necessarily to compare products, it would be a useful ability later on.

As mentioned previously, the application of boundaries is counterproductive when considering complex systems. However, for the sake of carrying out assessments and analysis within data and time constraints, boundaries are a necessity. The advantages of having boundaries to limit the scope of the analysis is simple – to be able to conduct analysis within a certain time frame using sufficient data in order to retain accuracy and reduce uncertainty as humanly as possible. Figure 21 shows the relevant boundaries that need to be set by the practitioner.

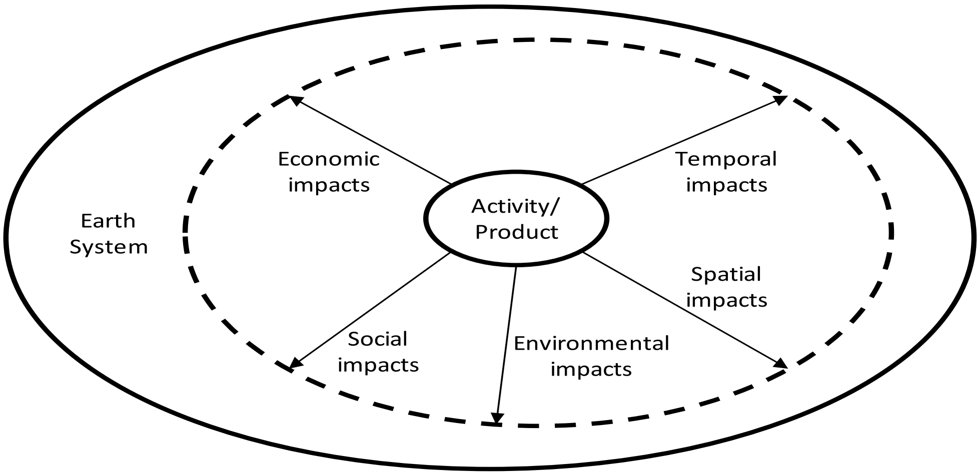

Figure 21: System boundaries to consider

Temporal impact boundary: Depending on the depth of the assessment, time should be considered from the present, incorporating analysis of current issues, to the future such that potential issues for the future can be identified. A life cycle perspective is advantageous when determining impacts of product with respect to time. However, LCA only includes time indirectly in terms of the life cycle stages of the product. The results from the impact assessment are given in the current context thus there is no differentiation between current and future impacts. This means that while it is possible to determine impacts per each stage of the life cycle, there is no indication of when the impacts are occurring in a real time context. Hence the temporal dimensions should consider inputs, outputs and impacts from cradle to beyond the grave, with specific time frames if possible, keeping in mind that some impacts are instantaneous while others can accumulate in the long term, or the impacts are seen after a time delay (e.g. carbon dioxide related global warming).

Spatial impact boundary: The geographical scope is significant when connecting the impacts to their sources, the affected parties, etc. Spatial differentiation can be conducted to divide the impacts/risks into three sections; site-specific (local), regional or global according to the type of impact. These should include connectivity to the mediums that are affected (land, water, air, etc.). The practitioner should be given the freedom to choose whether in-depth analysis is required for site-specific, regional, global or a combination of all three spatial contexts for analysis. For example, if the goal is related to the acid rain impact category, the practitioner may want to analyse site-specific impacts and since acid rain can affect a large region, regional impacts may also be necessary to determine the full impacts associated with their product service. Spatial context influences the type of data that is needed for the assessment where the practitioner may be required to collect site-specific data or purchase databases for use in the assessment.

Environmental, social and economic impact boundaries: Since the assessment is based on the strong sustainability model, it is difficult to place boundaries on the three systems as the economic system is a subset of the social system and the social system is a subset of the environmental system. Placing a boundary to exclude any one system is essentially a reduction compromising holism. Thus for the model to be considered a sustainability assessment, there should be no boundaries on these three systems. Basically, system boundaries define which unit processes would be included in the analysis. For the model, boundaries need be identified such that the analysis continues to retain holism and enable complexity to be taken into account. The application of boundaries serves as cut-off points and limits the scope of the analysis. While this may be prudent for large projects in order to save resources such as time and effort, a complete picture of the systems would require broad boundaries with little constraints. However, the issue is that it is not practical for industry to carry out such broad analysis when they are concentrated on day-to-day activities in the business world.

The boundaries for the environmental, economic and social impacts can be placed according to the choice of impact categories the practitioner of the model wishes to focus on after a complete assessment has been carried out. For example, where the main concern is the production of greenhouse gasses, then the practitioner can limit the analysis to global warming impacts by choosing the appropriate impact categories. While streamlined versions of the model may provide information for decision making, it will not be equivalent to a sustainability analysis. In the event where information and analysis of specific impacts, risks or systems are required, it is best to conduct a full holistic assessment and then present the results particular to the requirements. One advantage of this is that possible hidden impacts and risks may be revealed through a complete assessment. A disadvantage is the time and resources required to conduct the full assessment. It is thus up to the practitioner to choose the level of information required as well as the time and resources available for the assessment.

ALLOCATION

Allocation problems arise when a process is multifunctional, i.e. leads to multiple functions or products (Ekvall and Finnveden, 2001). With multiple functions or products, the environmental burdens need to be split up according to function or product. For example, allocation issues can arise during waste management or recycling where there is energy or material recovery as in the case of open-loop recycling where waste from one life cycle is recycled and used as input for another life cycle (Klöpffer, 1996; Babarenda Gamage et al., 2008). Allocation is a controversial topic in the LCA community with respect to the most logical way to allocate (Azapagic and Clift, 1999; Ekvall and Finnveden, 2001; Weidema, 2001). The question of how to allocate material (specifically aluminium) was put forth to the LCA forum (O2 online community) where a discussion was initiated to provide insight in the various means of allocation (O2, 2007). There are a number of ways to allocate burdens resulting in attributional and consequential LCA (Ekvall and Weidema, 2004; Heijungs and Guinée, 2007). If resources are incorrectly allocated, the results of the assessment would be flawed, resulting in significant issues for companies (Rebitzer et al., 2004).

ASSUMPTIONS AND KNOWN LIMITATIONS

Other elements of the model that highlight limitations need to be outlined in a transparent manner. Recommendations to eliminate limitations should also be investigated where sensitivity analysis can be carried out to indicate the possible effect of the limitation or assumption. Reiteration of the model with improved input can increase the robustness and accuracy of the results. Examples of assumptions include those relating to the scope of the life cycle and are closely related to potential limitations. Assuming that a proxy material would have equivalent properties as a material in the life cycle for which data cannot be found is a common assumption where proxy data are used to overcome limitations associated with data unavailability. Where data are unavailable, informed assumptions, i.e. ones that are close to reality as possible, may enhance the study. Other assumptions include omission of a life cycle stage that is considered to be of minor consequence, etc. Sensitivity analysis should be carried out to determine the effect of the assumptions where possible.

5.3.2 B: INVENTORY

The inventory, as described in previous chapters, consists of all the inputs and outputs related to a particular action or product in all the life cycle stages. The inventory data is collected and analysed according to the ISO standards for LCA. The data can be site-specific or they can contain generic information as available in databases that are commonly used. Alternatively, databases can be developed for specific processes according to geography. However, site specific data are advantageous to allow for a more accurate assessment (Ross and Evans, 2002). For best results a combination of data sources can be used to build the inventory, the priority given to site-specific data collected from the company and its suppliers.

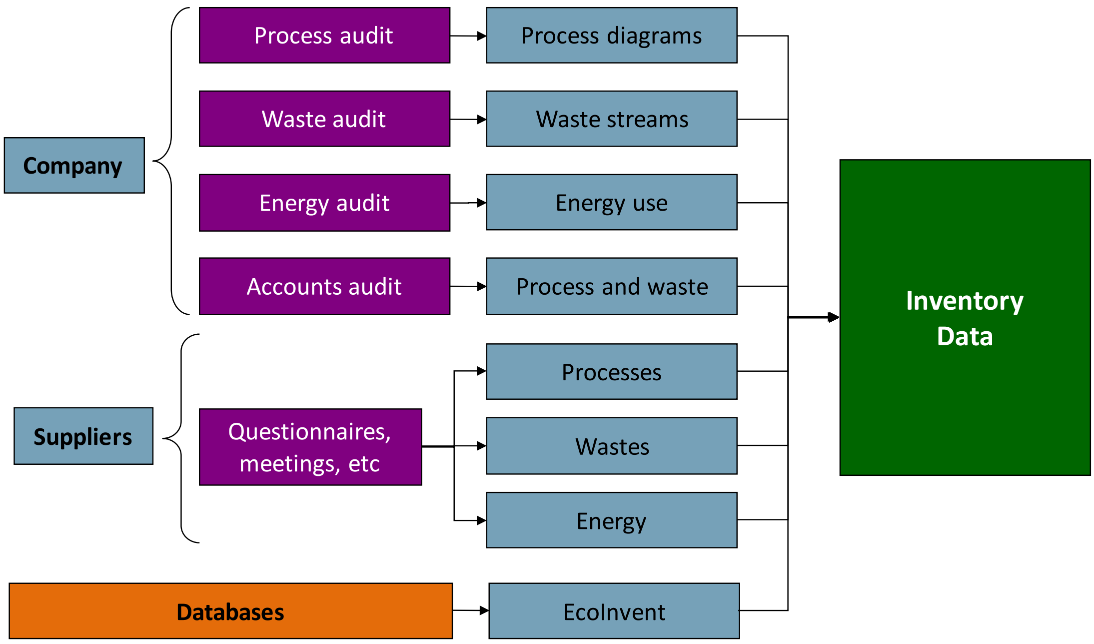

Figure 22: Sources of data for the inventory

The information gathered from audits and questionnaires as shown in Figure 22 would help populate the database of all environmental aspects of the model. The two other significant systems (social and economic) as well as the interconnections among the agents and the systems needs to be accounted and thus data for the social and economic inputs and outputs need to be collected too. Once they have been collected, there will be three datasets of inputs and outputs. There will be interconnections among the three and making those connections would be relevant to understanding the cause and effect of impacts and also may help explain the emergence of phenomenon if there are any. The inputs of the inventory can be thought of as being equivalent to the needs of the product and this relates to the operation and wellbeing of the system/s responsible for the product, i.e. the company as a subsystem of the economic social and environmental systems is dependent on inputs and to some extent, the outputs of their processes. Figure 23 illustrates the three sets of inventory if the assessment is carried out as shown in Figure 19.

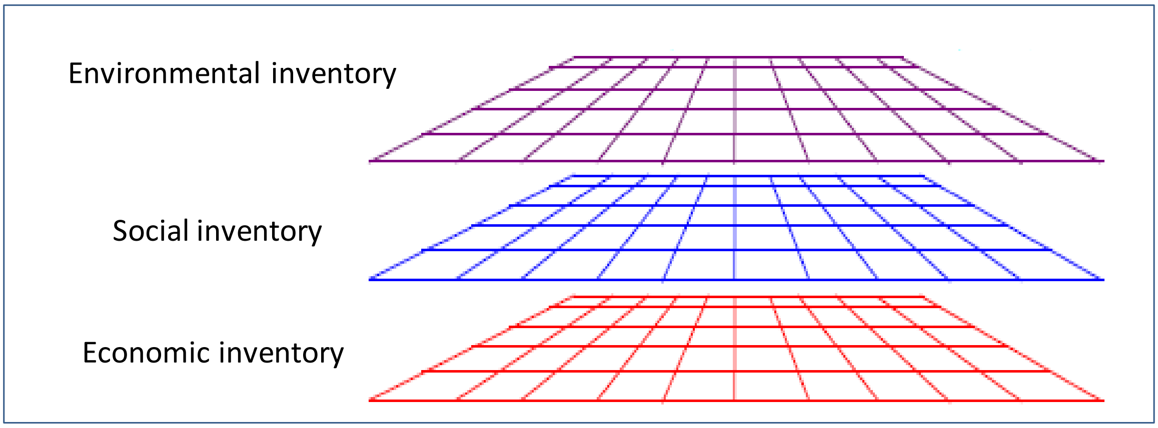

Figure 23: Inventory matrices for the three systems (environmental, social and economic)

Currently, there are databases per individual system (environmental, social, economic), however, there are no databases that link data from the three systems together thus the three separate inventories in Figure 23 represent the current state of inventories. As noted earlier, the separation of the three systems represents weak sustainability and consequently, this means that complexity with respect to interconnections and interactions of the systems and individual agents would be neglected. To overcome some of the limitations, an integrated systems model is proposed in Figure 24. The figure illustrates the possible interconnections within the overall system where the black lines represent an affiliation of one aspect of a system with another. These interconnections would need to be made manually as the current databases represent individual systems only.

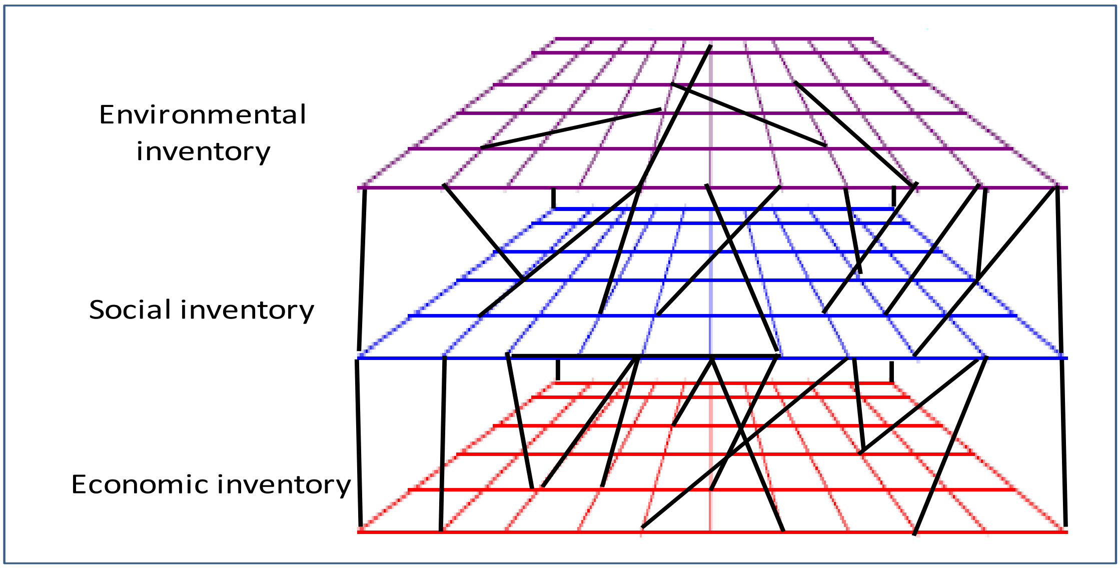

Figure 24: The inventory showing connections among the inputs and outputs of the overall system.

While the above integrated inventory database is an improvement to the use of separate databases per system, it is still based on weak sustainability, or a TBL approach and can lead to omission of many complex interactions. The ideal model for assessing sustainability, as given in Figure 20, represents strong sustainability and this requires inputs and outputs pertaining to all the systems and subsystems relevant to the product to be gathered holistically. Thus it is ideal to collect data on the three systems and present these in one single database, each dataset comprising of the environmental, social and economic inputs and output data pertaining each aspect of the product system. In order to have such a matrix of data for the whole system, the inventory stage will include the gathering of data for each of the selected systems. This means that the data records currently found in LCA databases need to be extended to include other systems that are relevant to the product.

The inventory step thus results in a vast database of information about the product showing inputs and outputs from system to system, system to subsystem, agent to agent, etc. The inputs are categorised into the type of medium they affect and this in turn helps to identify the sources of impact which in turn help determine whether the impacts would be local, regional or global, whether the impacts would affect the systems now or in the future, etc. at the impact assessment stage prior to identification of risks. Figure 25 shows some of the materials needed for the manufacture of steel. This only shows the inputs from the environment. All the connections to inputs and outputs for steel are made in the inventory record in existing databases. It is complex as it is, however, when the outputs are also taken into account, the complexity increases. When economic and social inputs and outputs are added, the complexity increases once more. With the increase of complexity, the amount of data that needs to be managed also increases. This means that a lot of time and effort would be required to examine each input, output and the interconnections among them. Note that the locations for the source of materials are not included in the existing databases since current LCA is based on global impacts. However, sources of resources are needed for spatial differentiation.

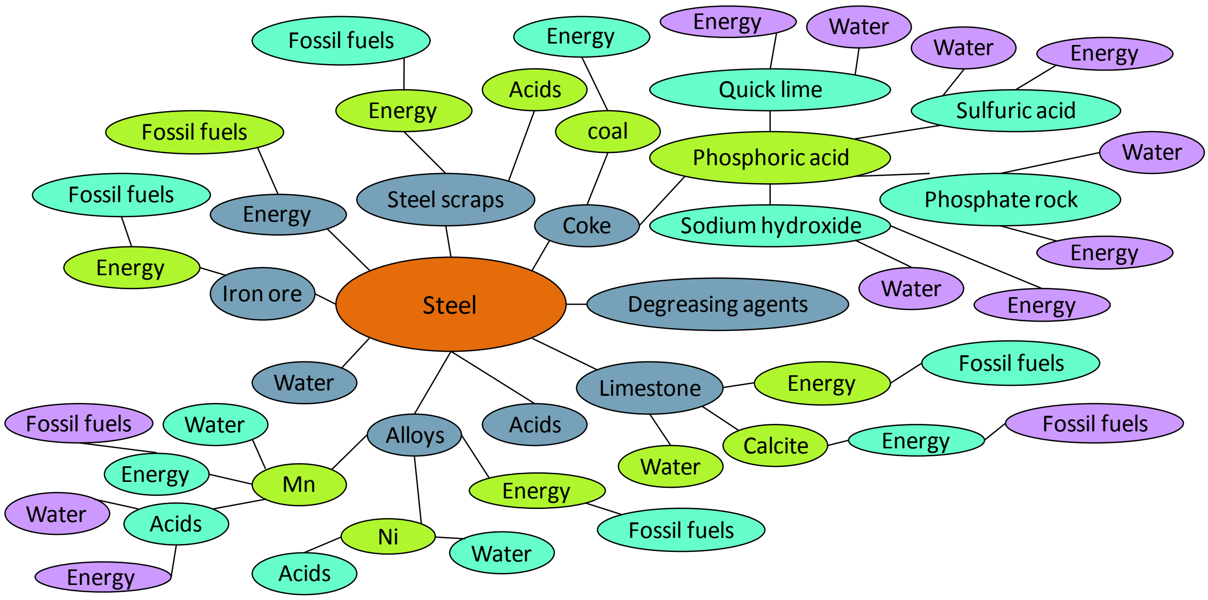

Figure 25: Example of the level of complexity with respect to inventory data

In order to minimise the number of inputs and outputs to consider, cut-off criteria can be implemented to allow the assessment to be concentrated on the most significant impacts, input and outputs of the life cycle. An example of a cut-off criteria procedure is to omit material that make up less than a certain percentage of the whole product; or to omit impacts that contribute less than a certain percentage of the total impact. This would work well for minimising the number of inputs and outputs to consider, however, some of the material neglected may have significant impacts even in small doses. There is no common recommended cut-off criterion where the choice of cut-off criterion is left up to the practitioner. However, there has been some research on the effect of process specific cut-off criteria for impacts on materials where the results show that a 4% cut off criteria accounted for 80% of the impacts at midpoint impact categories (Rebitzer and Jolliet, 2005). If data are readily available, it is best to include all unit processes for a complete LCA inventory. The result of the inventory stage is the analysis of the inventory. The analysis should highlight some of the significant connections among the resources in terms of the life cycle stages, inputs and outputs in such a way that the environmental, social and economic systems and their respective connections are mapped. This will be used in the next part of the model to identify risks after the impacts are assessed.

5.3.3 C: IMPACT ASSESSMENT

Impact assessment is useful for classifying inventory data and characterising them according to selected impact categories to identify what the potential impacts are, where they are coming from in terms of the life cycle stages, processes, materials, etc. Impact assessment can be carried out using existing impact assessment methods such as the EDIP 97 (Wenzel et al. 1997), EDIP 2003 (Hauschild and Potting, 2003, Potting and Hauschild, 2003), CML2001 (Guinée, 2001) EcoIndicator99 (Goedkoop et al., 2000), etc. These methods differ in terms of whether they are problem oriented (also known as midpoint) or damage oriented (or endpoint) type assessments (Dreyer et al., 2003). The midpoint method classifies flows into environmental themes (between emissions and damages) to which they contribute whereas the endpoint method models damage to environmental themes such as damage to human health, ecosystem health or resources (Figure 26).

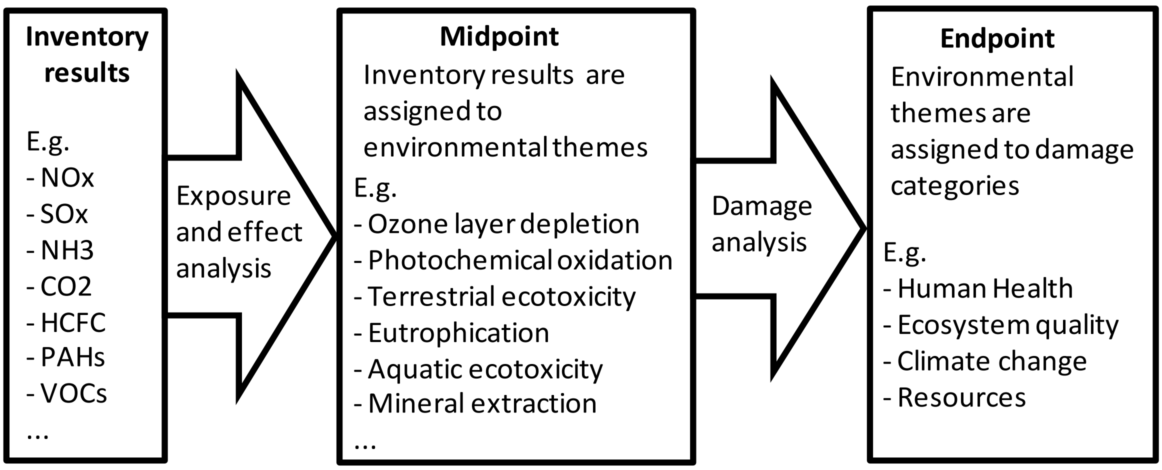

Figure 26: From LCI to midpoint and endpoint impacts

According to Bare et al. (2003), midpoint modelling results in less uncertainty as complexity of the modelling is reduced by minimizing assumptions, value choices, etc. Characterized results, (i.e. midpoint impacts) are sufficient according to ISO standards and they are also sufficient for this sustainability assessment model. One of the issues with LCA, as mentioned previously, is that it mainly considers environmental impacts, characterising the inventory inputs and outputs into impact categories as given in Table 10. These cover a number of relevant indicators however coverage of human social and economic is very limited.

Extending LCA to include the other systems is important to enable better understanding of complexity. This sustainability assessment model considers complexity in the risk assessment stage but first the cause of risk must be identified. The impact assessment results in characterized results indicating the environmental issues. To some extent these are risks from the inputs and outputs but they do not illustrate the interconnections among systems yet. In order to determine the interconnections, the risk assessment step is carried out. However, before that, significant risk from the characterized results must be identified. As with the integration by Sonnemann et al. (2004), the impact assessment step can be used to highlight significant impact contributing processes during a life cycle. The impact assessment step serves to pinpoint the most significant impacts per impact category and thus limit the scope of the study by focusing on the highest impact contributing processes. At this stage, impacts can also be differentiated according to media such as impacts to water, air, soil, etc.

Table 10: Common impact categories for LCA (Guinée et al., 2002)

Impact Category	Unit	Description
Abiotic depletion	kg Sb eq	Natural resource depletion including energy sources
Global warming (GWP100)	kg CO_2 eq	Contribution of a substance to the greenhouse effect
Ozone layer depletion (ODP)	kg CFC-11 eq	Thinning of the ozone layer as a result of anthropogenic emissions
Human toxicity	kg 1,4-DB eq	Impacts on human health due to toxic substances in the environment
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	Impacts of toxic substances on fresh water aquatic ecosystems
Marine aquatic ecotoxicity	kg 1,4-DB eq	Impacts of toxic substances on marine aquatic ecosystems
Terrestrial ecotoxicity	kg 1,4-DB eq	Impacts of toxic substances on terrestrial ecosystems
Photochemical oxidation	kg C_2H_4	Formation of reactive substances that can damage human health and ecosystems
Acidification	kg SO_2 eq	A wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials
Eutrophication	kg PO_4---eq	Impacts due to excessive levels of macronutrients in the environment from emissions of nutrients to air, water and soil

Identification of significant risk can be carried out in a procedure much like dominance analysis by Sonnemann et al. (2004). In the study by Sonnemann et al. (2004) dominance analysis and spatial differentiation is carried out after the impact assessment stage. The dominance analysis is carried out to determine the most significant media, processes and pollutant for further investigation. Note that some of the spatial differentiation in terms of the source of inputs has already been carried out in the inventory analysis stage for this model, especially in terms of material sources and processing. This is significant for onsite information when it comes to investigating the unique ecosystems in the impacted region if site specific cause and effect are to be found. The spatial differentiation with respect to the impact is to identify whether the impacts would be felt locally, regionally or globally. This becomes significant when considering issues such as land use, resource depletion and pollution where the impacts can differ in intensity accordingly.

The release of substances can have different impacts with respect to time and space. For example, release of hazardous substances into a river can cause poisoning of species at the site of discharge as well as downstream. With time, the dispersion would minimise the strength of the substance. Likewise, releasing large amounts of pollution at a given time would have different consequences from that of releasing it over a period of time. Time allows substances to dissipate but time also allows substances to accumulate depending on the properties of the substance. For example, pollutants that cause greenhouse effect accumulate with time even though the carbon cycle and photosynthesis help remove carbon from the atmosphere. Identifying where and when impacts occur can help plan to mitigate the effects. LCA deals mainly with global impacts, however, not all the impact categories lead to global concerns. For example, eutrophication and acidification are largely local and regional impacts and the time frame for the impacts are relatively short compared to impact such as global warming.

Table 11: Temporal and spatial differentiation of impact categories (modified from Stranddorf et al., 2005)

	Space			Time	
Impacts	**Global**	**Regional**	**Local**	**Current**	**Future**
Global warming	x				x
Stratospheric ozone depletion	x			x	x
Photochemical oxidant formation		x	x	x	
Acidification		x	x	x	
Nutrient enrichment		x	x	x	
Effects of waste heat water			x	x	
Ecotoxicity		x	x	x	x
Human toxicity		x	x	x	x
Odour			x	x	
Noise			x	x	
Radiation	x	x	x	x	x
Resource consumption	x	x	x	x	x
Land use			x	x	x
Waste			x	x	
Effects on eco-systems				x	

Spatial and temporal differentiation can be carried out using the information from Table 11 as shown in Figure 27. In order to remain holistic, all impact categories should undergo spatial and temporal differentiation after the impacts have been assigned to their respective media. As described earlier, assigning the impacts to the respective media would enable the impacts to be traced to their origins, thus highlighting the material or process that is responsible for the impacts. The resulting matrix contains all the data required for the system that is investigated where the identified impacts are equivalent to threats to the system.

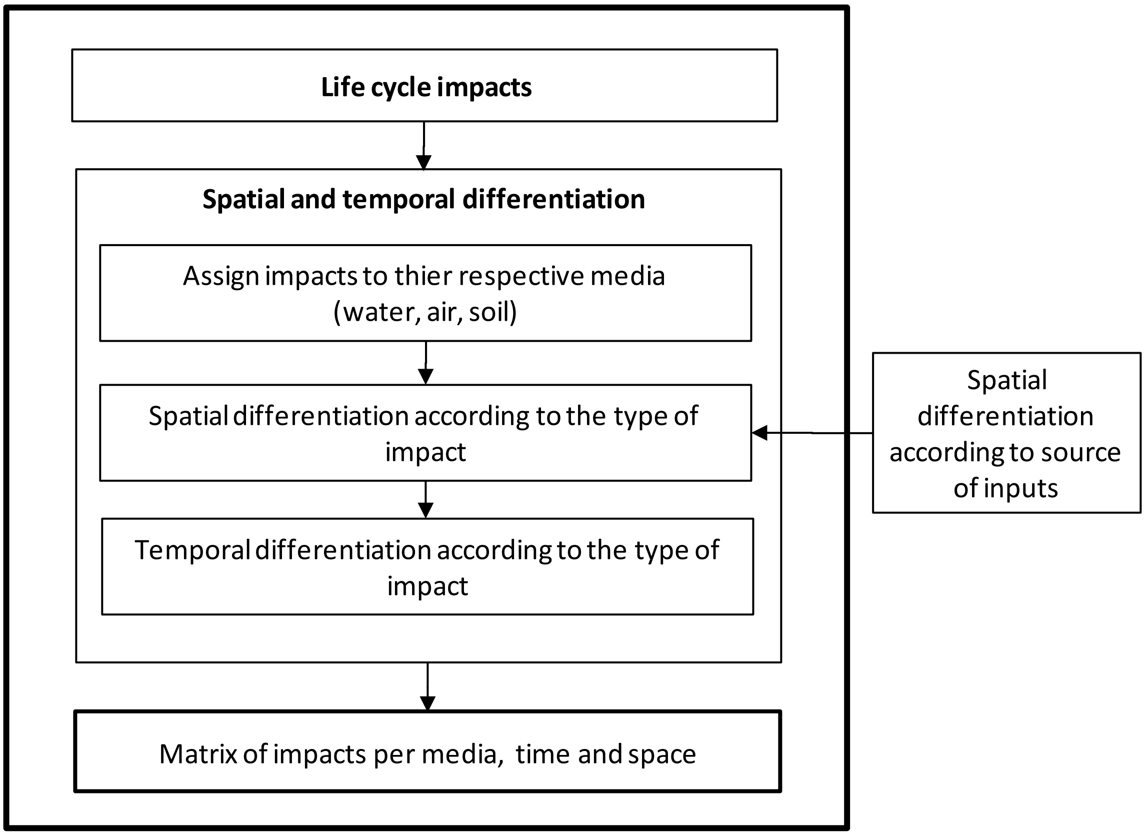

Figure 27: Spatial and temporal differentiation resulting in a matrix of impacts per media, time and space.

For a full assessment, all the impact categories used in the impact assessment stage would need to be investigated further resulting in a matrix of impacts with respect to the system assessed (Figure 28). There could be a multitude of impacts categories, and investigating them all may be time consuming thus streamlining may be required. In order to streamline the assessment, the practitioner can concentrate on one type of impact category if suitable. The choice of impact category to investigate further would depend on factors such as:

- The significance of the impact category in terms of local impact – for example if the system is located in an area where water is scarce, then the practitioner can choose the impacts that affect water as a medium for further investigation;
- The significance of the impact category towards global impact – for example if the company is interested in minimising global warming impacts in line with current debates on greenhouse gas emissions and carbon footprints, the global warming impact category can be analysed further.

The choice of impact category depends on company policy with respect to current and future needs, government policy, community and scientific interest, etc. The size of the final matrix would depend upon the number of impact categories chosen for further investigation. The resulting matrix in Figure 28 would contain vast amounts of data on the product. One of the issues with the life cycle inventory of this sort is its vastness. However that is to be expected due to the information needed to understand complex systems.

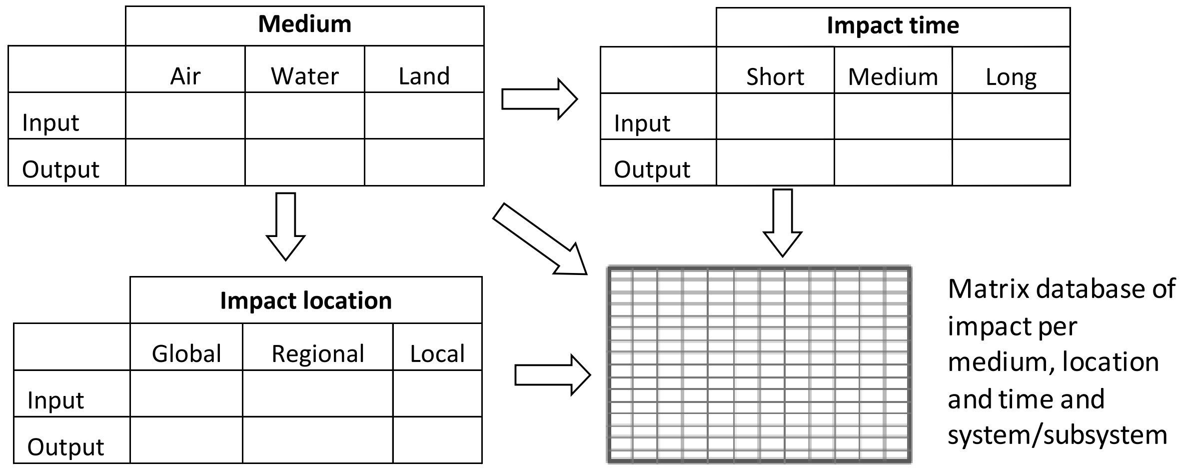

Figure 28: Classifying inventory data in terms of medium, location and time

5.3.4 D: RISK ANALYSIS

Once the significant impacts and the cause of these impacts are identified and traced to their origins, the next stage of the model is to conduct risk analysis. The risk analysis step consists of the following processes according to ISOI 31010/FDIS:

- Establish context;
- Risk identification;
- Consequence analysis;
- Qualitative, semi-quantitative or quantitative probability estimation;
- Assessing the effectiveness of any existing controls;
- Estimation the level of risk (evaluation); and
- Risk evaluation.

Using the results from the impact assessment stage, RA can be initiated using any of the appropriate techniques in Table 12. The first task is establishing the context of the analysis so that it is aligned with the overall goal and scope of the sustainability assessment. This is followed by identifying the sources of risk and then choosing the appropriate RA techniques to analyse risks. Examples in the form of case studies are provided in the Chapter 6 to illustrate the choice of RA technique as well as expected results for case study systems.

ESTABLISHING CONTEXT

The purpose of the RA is to determine risk that can disrupt vital characteristics of the complex system being investigated. The starting point of the analysis consists of the impacts identified as well as their sources, whether they are global impacts, whether the impacts change with time, etc. as per the impact matrix. Information on risk is added onto this matrix. The goal of the risk assessment is to determine and evaluate risk to the system from the identified environmental, social and economic impacts. This can be done in a two-step process:

- The first step is to identify and evaluate risks from the impacts themselves – i.e. how would the impact categories chosen affect sustainability? What are the consequences of the impact categories on the system under analysis? (How does an impact affect the product across the various systems?)
- The second step is to analyse the sources of the impact individually, make the connections from system to system so as to determine the level of risk associated with the sources of the impact. This step allows for locality specific risks to be evaluated since site specific data would be used.

Additionally, the internal and external context is to be identified. Since the assessment deals with complex systems, and the system analysed is one level of the overall complex system, external context would be significant with respect to how external risks can affect the system. Risks that affect the overall complex system can affect the system itself. Internal context refers to the risks that are owned by those responsible for the product system within a company and these needs to be determined to aid the function of the system and mitigate issues within the system that can impact upon other levels of systems. External risk for a company is associated with business drivers; competition; social, regulatory, cultural, etc. systems or subsystems; external stakeholders, etc. The internal risk context should take into account the structure of the company, internal stakeholders, resources and objectives of the company. Both external and internal contexts can affect the product system which is the object of the sustainability assessment.

RISK IDENTIFICATION AND ANALYSIS

As mentioned previously, there are two forms of risk or threat identification that can be carried out for the assessment. The risks can be categorised according to the incoming and outgoing threats as shown by Figure 29. The black arrows indicate risks from the processes and resources used by the product system and these are closely related to the impacts found at the impact assessment step.

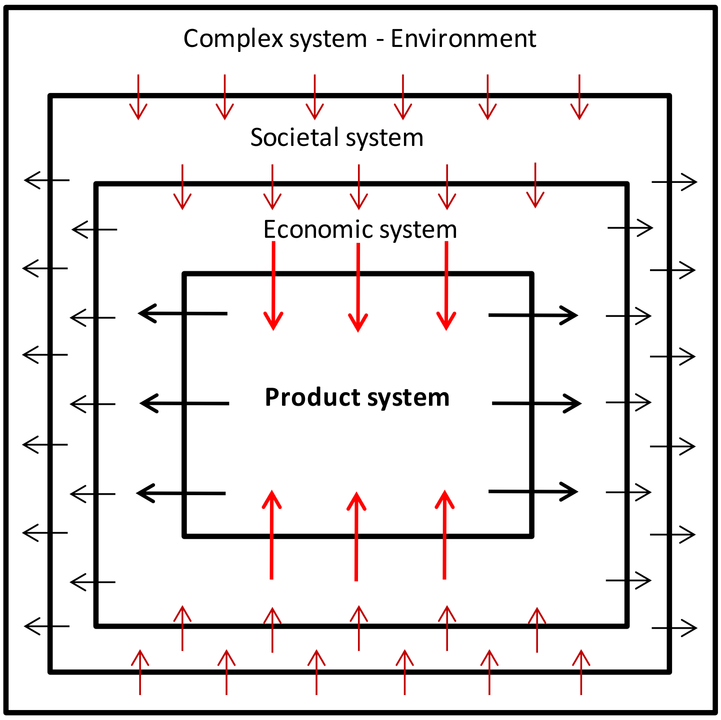

Figure 29: Incoming and outgoing risks related to needs of the product system

The outgoing risks (arrows in black) relate to the threats associated with the chosen impact categories, most of which are external or global risks. The risks associated with the impact categories can be used as a reference where further investigation is required to determine whether a particular impact category and hence risks associated with that category are relevant to the product system. Figure 30 illustrates the formation of a matrix with generic risk data pertaining to chosen impact categories. This is important for understanding the risks that may affect higher level systems which are connected to the product system.

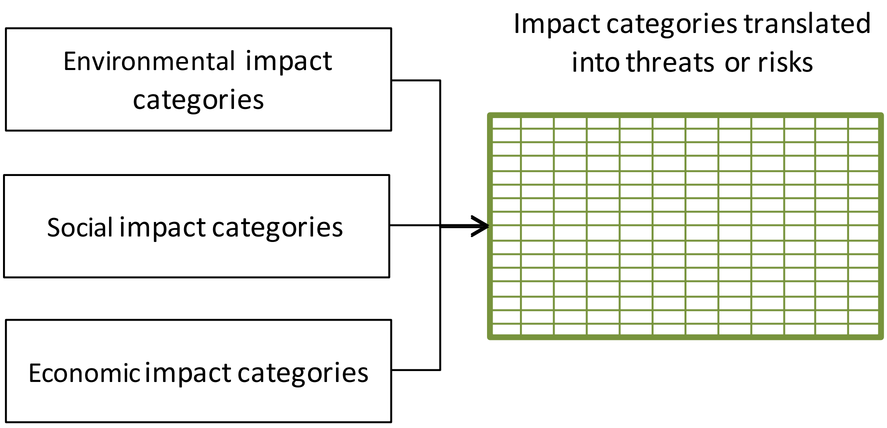

Figure 30: Risks related to selected impact categories

The arrows in red (Figure 29) indicate risk to the product system. These risks can be a direct result of the outgoing risk caused by the impacts from the product system; or it could be risks from the inner levels of the system including supply and needs of the system. The sources of the impacts identified earlier, i.e. resources or needs of the system, may highlight more localised threats that will help connect the impacts and risks to complex system characteristics and behaviour.

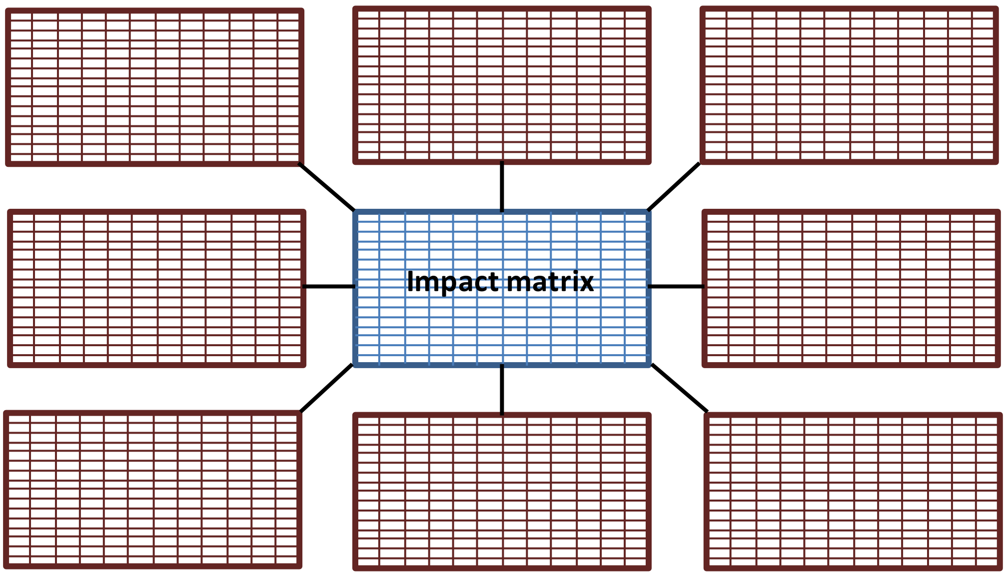

Figure 31: Risks to the product system as a result of risks pertaining to the needs of the system

Figure 31 illustrates the impact matrix that is used to generate information regarding risks from within the product system. The matrix of impacts is used to generate risk matrices for selected resources and processes spanning the social, environmental and economic systems with respect to location and time. These matrices each represent risk information pertaining to some aspect of the complex system. These risks are associated with the needs of the system rather than being the result from the impacts from the product system. Note that each resource identified would need to be analysed to determine the risks to the product system. All the threats, from the impacts as well as from the resources and process within the product system need to be analysed with respect to time and space.

The risk analysis is to be carried out on the source of the significant impacts that were identified at the impact assessment step. In order to reduce scope of the assessment, the number of significant impacts may be reduced to a manageable amount. This can be done via the use of cut off percentage as the practitioner sees fit, i.e. impact sources that account for more than 10% of the total impact per impact category. This is again equivalent to dominance analysis by Sonnemann et al. (2004) where the most significant impact producing substances are analysed further.

Risk analysis can be carried out qualitatively or quantitatively according to data availability. A combination of the two is recommended for best results however, there are many methods for analysing risk. ISO 31010/FDIS base the choice of risk analysis technique on data availability, effort and time constraints; complexity of the problem; and whether quantitative or qualitative output is desired. To ensure risk pertaining to all threats against the complex system is identified and analysed, a toolbox of risk assessment techniques is recommended. This toolbox consists of the following types of risk analysis techniques as found in ISO 31010/FDIS given in Table 12. The table contains information on the methods with respect to their ability to identify risk, analyse consequence, determine probability, determine level of risk, etc.

Table 12: Choice of risk analysis techniques (table constructed from data in ISO 31010/FDIS)

Method	Description	Risk ID	Consequence	Probability	Level of risk	Risk evaluation	Data requirement	Degree of uncertainty	Complexity	Quantitative
Look up methods										
Check-lists	Simple tool for risk identification	Strongly applicable	NA	NA	NA	NA	Low	Low	Low	No
Preliminary hazard analysis	Inductive method of analysis to identify hazards and hazardous situations	Strongly applicable	NA	NA	NA	NA	Low	High	Medium	No
Supporting methods										
Structured Interview and brainstorming	Collection of a broad set of ideas and evaluation, ranking them by a team	Strongly applicable	NA	NA	NA	NA	Low	Low	Low	No
Delphi technique	Collaborative technique where expert opinions support the source and influence identification, probability and consequence estimation and risk evaluation	Strongly applicable	NA	NA	NA	NA	Medium	Medium	Medium	No
SWIFT Structured "what-if")	Facilitated workshop to prompt a team to identify risks	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Medium	Medium	Any	No
Human reliability analysis (HRA)	Impact of humans on system performance to evaluate how human error influences the system	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Applicable	Medium	Medium	Medium	Yes
Scenario analysis										
Root cause analysis (single loss analysis)	A loss that has occurred is analysed to understand contributory causes and how the system or process can be improved to avoid such future losses	NA	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Medium	Low	Medium	No
Scenario analysis	future scenarios are identified through imagination or extrapolation from the present and different risks considered assuming each of these scenarios might occur	Strongly applicable	Strongly applicable	Applicable	Applicable	Applicable	Medium	High	Medium	No
Toxicological risk assessment	Hazards are identified and analysed together with pathways by which a specified target might be exposed to the hazard.	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	High	High	Medium	Yes
Business impact analysis	Analysis of how key disruption risks could affect an organization's operations	Applicable	Strongly applicable	Applicable	Applicable	Applicable	Medium	Medium	Medium	No
Fault tree analysis	Starts with undesired event and determines and graphically represents all the ways in which it could occur	Applicable	NA	Strongly applicable	Applicable	Applicable	High	High	Medium	Yes
Event tree analysis	Inductive reasoning to translate probabilities of different initiating events into possible outcomes	Applicable	Strongly applicable	Applicable	Applicable	NA	Medium	Medium	Medium	Yes
Cause/ Consequence analysis	A combination of fault and event tree analysis that allows inclusion of time delays	Applicable	Strongly applicable	Strongly applicable	Applicable	Applicable	High	Medium	High	Yes
Cause-and effect analysis	Contributing factors for an effect are identified through brainstorming and displayed in a tree structure or fishbone diagram	Strongly applicable	Strongly applicable	NA	NA	NA	Low	Low	Medium	No

Method	Description	Risk ID	Consequence	Probability	Level of risk	Risk evaluation	Data requirement	Degree of uncertainty	Complexity	Quantitative
Function analysis										
FMEA (Failure Mode and Effect Analysis)	Identifies failure modes and mechanisms, and their effects.	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Medium	Medium	Medium	Yes
FMCEA (Failure Mode and Critical Effect Analysis)	Identifies failure modes and mechanisms, and their effects and then criticality analyses which defines the significance of each failure mode, qualitatively, semi-qualitatively, or quantitatively	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Medium	Medium	Medium	Yes
Reliability centred maintenance	Identifies policies that should be implemented to manage failures	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Strongly applicable	Medium	Medium	Medium	Yes
Sneak analysis	Method for identifying design errors from latent hardware, software, or integrated conditions	Applicable	NA	NA	NA	NA	Medium	Medium	Medium	No
HAZOP (Hazard and operability studies)	Risk identification method that define possible deviations from the expected or intended performance	Strongly applicable	Strongly applicable	Applicable	Applicable	Applicable	Medium	High	High	No
HACCP (Hazard analysis and critical control points)	measures and monitors specific characteristics required to be within defined limits	Strongly applicable	Strongly applicable	NA	NA	Strongly applicable	Medium	Medium	Medium	No
Control assessment										
LOPA (Layers of protection analysis)	Method that allows the effectiveness of controls to be measured	Applicable	Strongly applicable	Applicable	Applicable	NA	Medium	Medium	Medium	Yes
Bow tie analysis	method for describing and analysing pathways of a risk from hazards to outcomes using diagrams	NA	Applicable	Strongly applicable	Strongly applicable	Applicable	Medium	High	Medium	Yes
Statistical methods										
Markov analysis	Used to analyse repairable complex systems that can exist in multiple states	Applicable	Strongly applicable	NA	NA	NA	High	Low	High	Yes
Monte-Carlo analysis	used to establish the aggregate variation in a system resulting from variations in the system using triangular distributions or beta distributions	NA	NA	NA	NA	Strongly applicable	High	Low	High	Yes
Bayesian analysis	Prior distribution data is used and relied upon to assess the probability of the result by modelling cause-and-effect via probabilistic relationships	NA	Strongly applicable	NA	NA	Strongly applicable	High	Low	High	Yes

In order to obtain sufficient information on the risks, it is preferred that the method/s selected for use is at least able to identify risk, determine consequence and probability to some extent. This would help determine the level of risk as well as allow risks to be evaluated with respect to the goal of the assessment. It would be preferable to choose a method that does not have a high data requirement. However, data correlates to the accuracy or the assessment and hence the more reliable data there is, the less uncertainty due to unknowns. In order to enable designers and engineers to apply the model, it should be simple yet with lesser degree of uncertainty. Thus it is a matter of choosing the risk assessment method that is best suited for the practitioner, audience and goal of the assessment.

RISK EVALUATION

After analysis, the risks are to be evaluated by prioritising them to allow for treatment of risk. The risks are compared with the goal of the system to determine the magnitude of the risk. A table consisting of predetermined criteria in terms of what is acceptable and what is unacceptable such as that given in Figure 32 is used to evaluate the risk. The result of the risk evaluation identifies the risks that are to be treated, prioritising them according to the type of consequence and the likelihood of the risk event occurring. While the probability of a risk event depends on the type of event, as well as historic data, the consequence is closely related to system limits. It is assumed that the closer to the limits, the greater the chance of system failure which is assumed to be the highest possible consequence for the system being assessed.

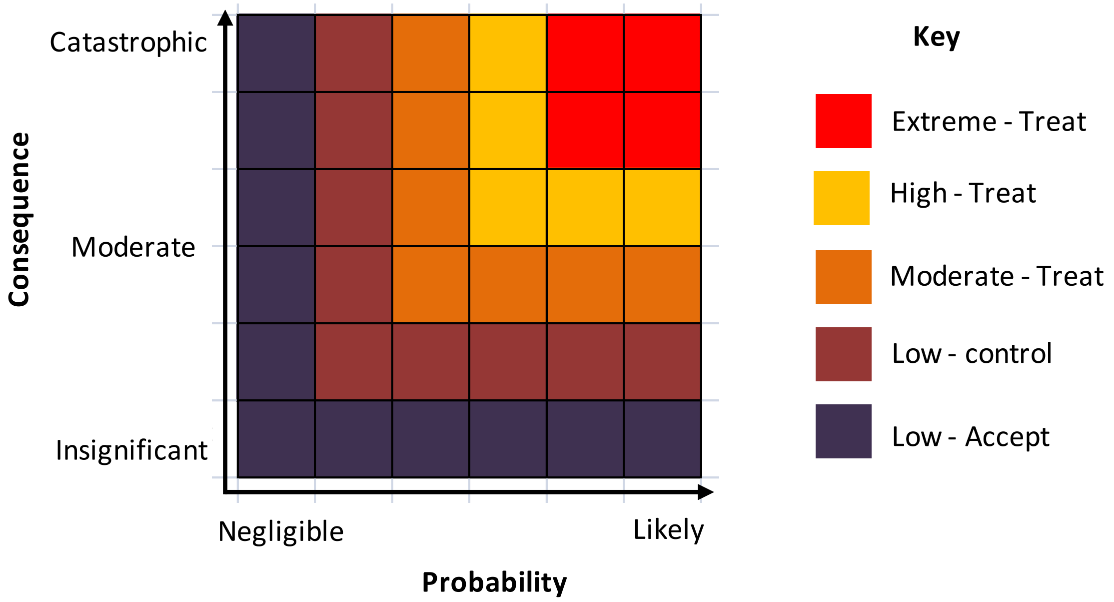

Figure 32: Risk model for evaluating risks

The risk evaluation step provides the final significant sets of results for the model (the other significant result is the impact matrix populated with data on the impact, the affected medium, location and time frame together with identified risks). This result may indicate the points of maximum unsustainability. The risk evaluation consists of the results to be presented to management in order for them to realize the risks faced by the product system as well as the risks from the product system to other system levels. It is this result that would prompt action (treatment) and ideally, the action should initiate another iteration of the process to determine whether it made the situation change for the better or worse. The risk model given in Figure 32 is two dimensional, considering probability and consequence of risk at a given time. The model may be improved by accounting for changes with time.

Time, a third dimension, can be added to the risk evaluation model where probability theory is utilized to determine patterns of risk according to risk type. Risks can be differentiated according to whether impacts accumulate over time or whether the impacts dissipate with time. Figure 33 illustrates a potential risk model for risk that accumulates with time.

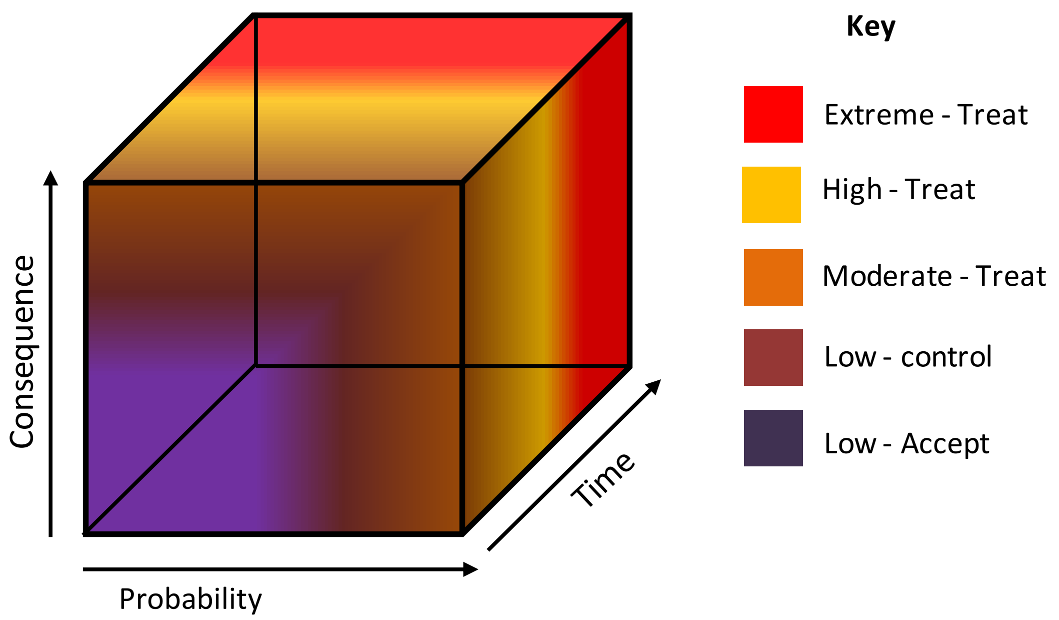

Figure 33: Risk model for evaluating risks changing with time (accumulation)

Different models to reflect the change in risk may be developed to evaluate risk on a case by case basis. The cases would depend on the different spatial dimensions which are able to influence the rates of accumulation or dissipation. I.e. risk at one location may not necessarily be the same as at another because different locations can have different systems and agents that may interact differently leading to different outcomes. For example, water contamination in a specific location in a drought stricken region would have different impact to water contamination in an area where multiple sources of water exist. Likewise, different ecosystems are able to remove toxic substances at different rates while others may lead to accumulation of the substance. These differences would need to be accounted for by having greater understanding of systems at different spatial dimensions.

5.3.5 E: RISK TREATMENT; F: COMMUNICATION; AND G: MONITORING

Risk treatment is the stage at which action can be taken with respect to the evaluated risks. There are four ways in which risk can be treated:

- Accept – risks are accepted when the damage is inconsequential, can be transferred, or until mitigation is possible;
- Avoid – means to control the likelihood of risk event occurring by avoiding certain tasks with high likelihood or high consequence;
- Transfer – risks that can be transferred to a third party, e.g. insurance; and
- Mitigate – reduce or eliminate the risk events that can cause significant damage.

Type of mitigation depends upon the following factors:

- Whether the risk is within the control of the practitioner or company;
- The cost of risk treatment;
- The resources needed to treat risk; and
- The possible alternatives to minimise or eliminate risk.

The risk treatments can range from avoiding the risk, removing the risk source, changing the consequences and the likelihood of the risk event occurring, sharing or transferring the risk, working with the risk, monitoring the risk, avoiding the risk, etc. The choice of risk treatment is left up to the stakeholders and should be implemented on a case by case basis as each risk event may have unique and complex means of treatment.

Communication and consultation among the relevant stakeholders should be carried out at each stage of the model in order to obtain input on the assessment. Additionally, the results from the assessment need to be communicated to various stakeholders in a clear and concise manner. The results need to be transparent with respect to the processes undertaken to achieve them. The results can be communicated in terms of a risk matrix together with information on the impacts, sources and timeframes, etc. Communication internally and externally is vital for management of risk and since sustainability of complex systems is one of the goals of the assessment, a wide range of experts should be made aware of the process and results in order to obtain feedback.

Monitoring and reviewing the assessment is action based where the activities pertaining to risk treatment and the consequent effects are monitored in order to determine whether the treatment methods and policies are effective. Risk is dynamic, changing with input or action. In order to account for the dynamic nature of risk, the processes within the model should be reiterated as new information is obtained. New information would highlight new risks and lead to greater understanding of the characteristics of the complex system.

5.4 CHAPTER CONCLUSIONS

The first section of this chapter presents existing work on integrated models containing RA and LCA. These works were carried out with the goal of extending or improving either LCA or RA and thus the purpose of integration for the model presented in this thesis is different to earlier works. Overall, research has been focussed on improving the methods, particularly in finding solutions to the lack of spatial resolution in LCA. There was no mention of the temporal aspect though that may be catered to by the investigation of the lifecycle to some extent. The introduction of RA either as ERA or HERA helps to determine the location where the impact occurs (local/regional) with respect to the consequences of the impact at the specific locations. The significance of the methods reviewed is in the different ways that the two techniques can be integrated.

The purpose of the integrated model presented in the later sections of this chapter is to assess sustainability of a complex system. A significant aspect of LCA is the use of the functional unit where the function of the product is used as a reference for comparative purposes. The unit process representing the functional unit is included in full with other relevant unit processes partially included thus making LCA an attribution mode of analysis. Given that the functional unit represents the product, and hence the relevant process units would be targeted during the assessment, the attribution analysis would help scope the assessment down to the most relevant process units of the life cycle. On the other hand, the attribution mode may be disadvantageous since it may affect holism by not considering all unit processes fully. Since the new model begins with LCA, and the functional unit concept is intact in the goal and scope stage, the new model is expected to be considered as an attribution mode analysis. Carrying out the assessment in terms of a full mode analysis may mean that more processes are assessed in detail, however, there are issues with respect to what processes will be excluded.

The final model presented in the chapter is a hybrid model that uses the results of one component of the assessment, the LCA, as input data for another component (RA). The model progresses from a reduced version consisting of streamlined assessments with respect to the systems chosen for assessment, to a holistic version which encompasses all three relevant systems (environmental, social and economic) from initiation (inventory) to completion (risk evaluation).The model follows the LCA steps with integrated inventory up until impact assessment spanning all three system after which the impacts are analysed to determine the risks from the chosen impact categories. The impact are also analysed to determine the significant sources of the impacts and how these impact sources can threaten the system. There are various ways of streamlining the assessment, ranging from using separate data records in the inventory to reducing the risks according to each system. While the practitioner needs to be aware of the shortcomings of streamlined assessments in general, such assessments can be very useful in providing preliminary accounts of system sustainability.

CHAPTER 6: CASE STUDY AND RESULTS

This chapter contains the results from implementing the model via case study products in the office furniture sector. Streamlined versions of the model are used to illustrate how the various components of the model can give information regarding sustainability. The case studies are also a pilot on how the model may be used by designers or engineers of a small or medium sized enterprise. The case study products were designed and manufactured by a company called Formway Furniture Ltd.

Formway Furniture was founded in 1956 as Petone Engineering, manufacturing steel framed furniture for the New Zealand market (Formway Furniture, 2004; Hales and Gooch, 2004). Formway is now an office furniture designer and manufacturer that licenses its products internationally due to some innovative designs created through changing the original manufacturing focus into a design focus. Formway products include workstations (FREE, GRID, etc.), chairs (LIFE, ARQ, KEY, etc.), storage systems (TRAFFIC), screens (FREE, GRID, etc.), etc. (Figure 34). Formway assembles products for the Australasian market while licensed partners cater for the international market.

Figure 34: Formway products featuring GRID workstation system and screens, LIFE chairs and TRAFFIC storage

As a NZ based company, Formway has a strong environmental focus and has been working towards a certified Environmental Management System (ISO 14000). Formway has taken a leadership role in sustainable development within New Zealand and as such their incorporation of EcoDesign concepts in the design process resulted in the LIFE chair in 2000. Their products are at the forefront of environmentally responsible products, incorporating numerous Eco-friendly principles such as reduce, reuse, recycle, (Lewis et al. 2001) disassemble, etc. planned right from the design stage of the product. Formway earned numerous awards including the "Sustainable Design Gold Award" in recognition of the LIFE chair at the IIDEX/NeoCon, in 2002 (Formway, 2004). International Interior Design Exposition (IIDEX) is a prestigious design exposition and conference held in Canada (IIDEX/NeoCon, 2011). Additionally, Formway's LIFE chair is certified by Good Environmental Choice NZ in the furniture and fittings category (Licence No 3208042). According to FRST (n.d.) "LIFE chair now accounts for about 20 per cent of Formway's annual revenue of around NZ$45 million, two-thirds of which comes from export sales."

With respect to operations, Formway employs up to 250 people in New Zealand and Australia. This includes a dedicated research and development team of approximately 14 staff responsible for the design and testing of new products. The budget for research and development for the year 2004 was approximately $3 million. For the same year, revenue totalled approximately $37 million. In terms of manufacturing operations, Formway has two manufacturing facilities within NZ, one of which manufactures the LIFE chair. Within these facilities, Formway consumes a mix of electricity and gas for manufacturing. Electricity and gas consumption fluctuates as the facility manufactures according to demand which is reflected in the number of successful tenders. Typically, usage fluctuates from 30000 to 70000 kWh of electricity and 150-750 GJ of gas, primarily used for powder coating of other products. Since Formway's LIFE chair components are made to specification and transported to the Gracefield Road facility for assembly, wastes associated with the product are limited to cardboard and plastic wrap. Formway sends metal waste material for recycling.

Formway Furniture's competitors include internationally based designers such as Herman Miller, Steelcase Inc., Teknion, Haworth Office Furniture, etc. A few of these competitors have carried out LCA studies and Steelcase Inc. has published results for two seating products as per Table 13.

Table 13: Comparison of competitor products (Babarenda Gamage et al., 2008; Spitzley et al. 2006; Steelcase, 2004)

Product	**LIFE -GFN** 	**Siento** 	**Think** 
Brand	Formway	Steelcase	Steelcase
Warrenty	10 years, 3 shift	12 years	12 years
LCA study	Full	Yes	Yes
Functional unit	Provision of comfortable office seating, with the features stated in the product description, over a period of 10 years in line with the product warranty	30 years of ergonomic executive seating in a wood office environment	Provision of comfortable office seating – with the features stated in the product description – for an average person (45 – 110 kg) for 8 hours a day, 5 days a week over a lifetime period of 15 years.
Impact Assessment method	CML2	Tool for the reduction and assessment of chemical and other environmental impacts (TRACI)	EDIP
GWP as % relative to LIFE chair with aluminium base	92%	62%	58%
Limitations	Aluminium with the world average recycled content of 34% was used. It was later found that the aluminium used in the LIFE chair is 100% recycled	The time period of 30 years used as the functional unit requires explanation since the warranty period is only 12 years	NA
End of life	Over 90% recycleable	Up to 91% recycleable	Up to 99% recycleable
EPD	No	No	Yes
Product certification	Greenguard, Good Environmetnal Choice NZ	NA	Greenguard, Cradle to Cradle

6.1 CASE STUDY METHODOLOGY

As noted previously, the case studies will illustrate the use of the new model, each showing different goals and issues associated with the product. There are six case study products, two of which are included in this chapter with the remaining four presented in Appendices. The first case study is a complete form of the model's application and the others are more streamlined to highlight different aspects of the model. The office furniture is manufactured from components that are imported from local and international suppliers. The case study product systems assessed include that of the LIFE chair (results presented as part of the thesis); Free and Grid desks; Traffic storage units; and Screens. The results for the desks, storage units and screens are available as separate reports. The methodology for implementing the model is as follows:

1. Define goal and scope of the assessment;
2. Collect inventory data and analyse data;
3. Conduct impact assessment to determine impacts along the lifecycle of the product system;
4. Identify risk associated with the impact categories as well as the significant impact contributing resources and processes; and
5. Analyse and evaluate the risk.

Treatment of risk is also considered as a short descriptive section in Chapter 7.

6.1.1 DATA FOR THE MODEL

In order to carry out the above, data need to be gathered to better understand the product systems. This involves mapping out the processes within the company as well as those from supplier processes. For information on the product, two questionnaires were used. The aim of the two questionnaires was to obtain site specific data on processes used by suppliers in order to build a site specific inventory. These questionnaires were developed in collaboration with Formway Furniture and work to obtain information from suppliers using the first questionnaire was underway when this research commenced. The first questionnaire is found in Appendix A. A second shorter questionnaire was formed to minimise the workload by NZ suppliers, most of who struggled with the first more comprehensive questionnaire. The second questionnaire was designed to confirm some of the significant data for use in the inventory (found in Appendix B). The questionnaires were sent to all suppliers where the components make up more than 1% of the product in weight.

Information on Formway manufacturing processes within the company included material inputs and outputs via site visits together with mapping of processes, bill of materials and discussion with design and engineering staff. Digital site maps and process diagrams were also developed during this research. Additionally, a number of audits to determine wastes and recycling were also conducted. The type of information obtained during the case study research is presented in Chapter 6 for the Life case study. Relevant staff members who were involved in the company's RA provided information on the risks associated with different departments of the company (corporate, process, environmental, design, etc.). Examples of questions related to discussion topics are found in Appendix C. The results from these discussions are given below and summarised in Table 14 identifying the significant risks or success factors for the company. These discussions were carried out to obtain a good understanding of the risks the company was already aware of and how they may be treating those risks. Furthermore, the discussion showed that achieving sales targets, developing new product, maintaining old product, production and sourcing of materials, environmental sustainability were among some of the critical risk/success factors for the company:

- **<u>Achieving sales targets</u>**

  From an economic perspective, yearly sales targets/ budget outline the company's revenue. In the event that marketing (sales) targets are not met, reduction of the company size is required for on-going operation. Hence, economic impact affects the social construct of the company. To a large extent, this phenomenon is mitigated through competing in multiple markets (Australasia, American, etc.).

- **<u>New products, maintaining current product relevance and customer satisfaction</u>**

  From a design perspective, the product relevance with respect to market requirements is significant in maintaining sales targets. Hence, connecting consumer preference with future design projects, as well as enhancements of existing products, is a major requirement in maintaining competitiveness.

- **<u>Production and sourcing</u>**

  The complexity in production and sourcing is seen as a major risk to production. Aspects such as global fluctuations in currency and cost of labour and infrastructure are considered risk factors. One of the proposed methods to reduce this risk is outsourcing; however, this introduces new risks especially pertaining to quality.

- **Environment and sustainability**

  From an environmental perspective, one of the largest risks considered is that customers may not believe that the company is serious about environmental and sustainability issues. Hence 'walking the talk' is imperative. Also, costs associated to energy are seen as a major risk factor.

Other significant risks (short to long term) to business according to the Corporate, Operations, Design and Environmental Managers are given in Table 14.

Table 14: Risk factors according to Formway management

Corporate	Operations	Design	Environmental
• Making order budget – maintains overhead structure • Not getting government funding • IFOTIS – In Full, on Time and in Spec to customers • New products and acceptance • Enhancements and customer demand	• Cost of labour vs. productivity • Quality of components • Supplier reliability • Material pricing • Cost of utilities – natural gas • Price of our product vs. competitor product • Logistics – transport modes, fuel costs, distances • Cost of capital – equipment, etc.	• IP infringements • New material • Time frames – design of product • Exchange rate • Supply chain – sourcing world wide • Natural disasters (earthquakes – Wellington) • Recession • Competitor products • Sustainability awards	• Green trend may disappear if customer interest dwindle • Cost of oil • Cost of energy and security of energy supply • Cost of alternative energy • Raw material supply uncertainty (plastics) • Resource scarcity (China) • Climate change

From a planning point of view, it was found that Formway considers risk to business mainly from a short to medium term perspective. The short term consists of planning for a 6 months to 1 year period considered as the Annual Plan. The medium term ranges from 1 to 5 years (depending on the business aspect considered) and is considered in the Strategic Plan. Long-term aspects of sustainability are, as yet, not addressed to a great extent. From the discussions, the following Formway goals in terms of sustainability were identified for the short, medium and long term.

- **Short term:**
  - To gain a good understanding of the importance of sustainability issues; and
  - Affordability in terms of operations as well as sustainably priced products.

- **Medium Term:**
  - To become leaders in the office furniture industry; and
  - To attain “Benchmark” status for Formway product.
- **Long Term:**
  - To respond to customer issues relating to sustainability;
  - To manage the social impacts associated with trends towards outsourcing production and assembly to developing economies; and
  - To design and produce truly sustainable products.

This exercise highlighted that significant aspects of the company operation contain elements of risk and sustainability that need to be addressed, regardless of whether at a formal or informal level.

6.2 CASE STUDY – LIFE CHAIR

LIFE stands for Light, Intuitive, Flexible and Environmental. The LIFE chair is designed for different work environments; therefore, there are a number of models available. The main distinction in the models for the purpose of this study is made according to the base of the chair, which comes in either aluminium or Glass Filled Nylon (GFN) (Figure 35). The two models weigh approximately 18 and 17 kg, respectively. The percentage material composition for the two chair models is given in Table 15. The most significant difference between the two LIFE models is their aluminium and GFN contents: the aluminium base model has approximately 2kg more aluminium by weight than the GFN base model, and the GFN base model has approximately 1.5 kg more GFN than the aluminium base model.

	Component	Material
1 -	Mesh back	Polyester
2 -	Back frame	Glass filled nylon
3 -	Lumbar	ABS
4 -	Lumbar hinge	Nylon
5 -	Arm	Aluminium
6 -	Arm pads	Polyurethane foam
7 -	Arm components	Acetal
8 -	Seat cushion	Polyurethane foam
9 -	Seat moulding	Hytrel Crastin(PBT)
10 -	Seat carriage	Aluminium
11 -	Mechanism assembly	Aluminium
12 -	Gas spring tube	Steel
13 -	Base	Nylon / aluminium
14 -	Castors	Nylon
15 -	Castor axle, spring	Zinc
	Springs, bolts, pivots	Steel

Figure 35: Main components and material make up for the LIFE chair

The material breakdown of the LIFE chair with the aluminium and GFN bases are given in Table 15. From this table, it is evident that aluminium comprises of up to approximately 60% of the total weight for LIFE chair with aluminium base and approximately 50% of the LIFE chair with GFN base. Furthermore, GFN makes up 6% of the aluminium model and over 15% in the GFN model. This is the key distinction between the two chair models. The material compositions for the two chair models are compared in Figure 36.

Table 15: Material composition of the LIFE chair models with aluminium and GFN bases

	Weight component (g)		% Weight component	
Material	**Aluminium base chair**	**GFN base chair**	**Aluminium base chair**	**GFN base chair**
Aluminium	10680	8460	59.3	49.8
Steel	1633	1633	9.1	9.6
Glass filled nylon (GFN)	1135	2660	6.3	15.6
Polypropylene	145	145	0.8	0.9
Glass filled polypropylene	50	50	0.3	0.3
PUR (polyurethane)	820	820	4.6	4.8
POM (Acetyl)	318	318	1.8	1.9
ABS	375	375	2.1	2.2
Fabric	140	140	0.8	0.8
Hytrel	1285	1285	7.1	7.6
PA6 (nylon)	398	398	2.2	2.3
Packaging	1020	1000	5.7	4.2
Total	**18000**	**17000**	**100**	**100**

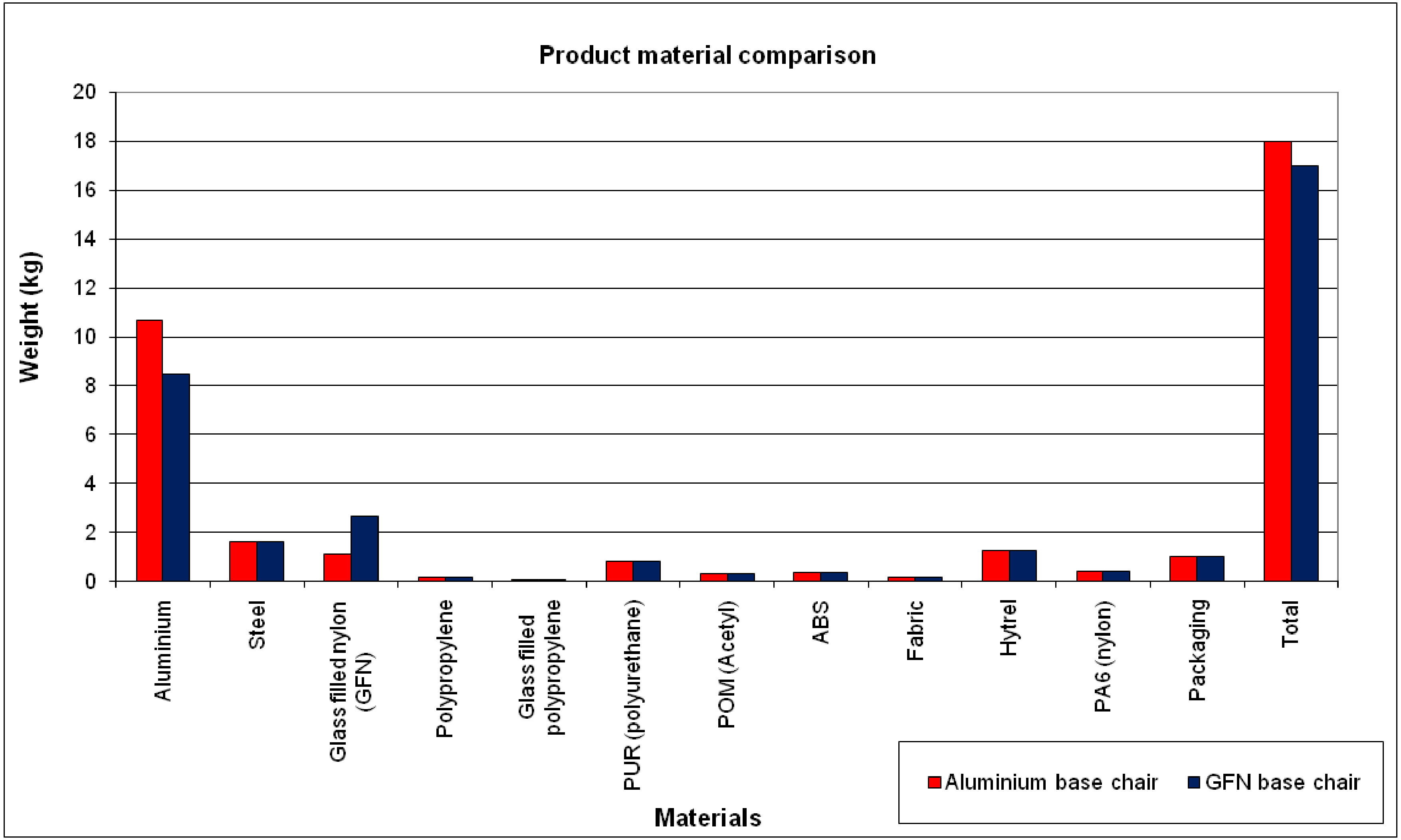

Figure 36: Comparison of LIFE material composition with aluminium and GFN bases

With respect to packaging material, since there are more polished aluminium surfaces for the aluminium chair model, it has some extra packaging for protection. The respective packaging composition is 20% thin film packaging; and 80% cardboard. The materials that can be recycled at the end of life are given in Table 16. Technically, over 90% of both types of LIFE chair can be recycled.

Table 16: Recyclable content of the LIFE chair

	LIFE with aluminium base		LIFE with GFN base	
Material	**% Weight component**	**Recyclable?**	**% Weight component**	**Recyclable?**
Aluminium	59.3	Yes	49.8	Yes
Steel	9.1	Yes	9.6	Yes
Glass filled nylon (GFN)	6.3	Yes	15.6	Yes
Polypropylene	0.8	No	0.9	No
Glass filled polypropylene	0.3	No	0.3	No
PUR (polyurethane)	4.6	Yes/No	4.8	Yes/No
POM (Acetyl)	1.8	No	1.9	No
ABS	2.1	No	2.2	No
Fabric	0.8	No	0.8	No
TEEE + PBT (Hytrel-Crastin)	7.1	No	7.6	No
PA6 (nylon)	2.2	Yes	2.3	Yes
Other (Packaging)	5.7	Yes	4.2	Yes
Total	**100.0**		**100.0**	

6.2.1 GOAL AND SCOPE DEFINITION

The goal of the case study is to assess sustainability of the LIFE chair system. This can be achieved via two further aims:

1. To develop a better understanding of the life cycle environmental impacts associated with the LIFE chair where the specific LCA related goals are to:
    a. Determine environmental hotspots in the life cycle of the two models of LIFE chair (one with aluminium base and the other with glass-filled nylon (GFN) base);
    b. Compare the life cycle environmental impacts of the two models of LIFE chair; and
    c. Compare alternative potential waste-management scenarios for the two models of LIFE chair; and
2. To carry out necessary risk assessments to determine risks to and from the product system.

The first and second goals inform Formway's environmental design improvement initiatives by providing detailed information about the environmental impacts of each chair model. The third goal was identified as a specific focus within the LCA study because Formway is actively investigating the best end-of-life (EOL) strategy for the LIFE chairs as part of a company stewardship programme. Initially, a streamlined version of this LCA study (Babarenda Gamage and Boyle, 2006) was conducted using EcoIndicator99 methodology, and this was extended to the final study which includes all life cycle stages reported in the paper by Babarenda Gamage et al. (2008) using CML2. Furthermore, sensitivity analysis was carried out to determine sensitivity to aluminium recycled content.

The scope of the study is aimed at doing a quantitative LCA that includes all possible processes from cradle to grave within practical limitations. The inventory of inputs and outputs for each product can be categorized into the following sub-systems:

- Baseline scenario:
    - All materials included in study; and
    - Lifecycle stages included in study:
        - Raw material extraction and processing;
        - Manufacture of components by suppliers;
        - Transport of components from suppliers to Formway;
        - Assembly of product by Formway;
        - Packaging of product by Formway;
        - Transport of product to customer;
        - Use of product; and
        - Transport and Landfilling of product at end of life.

Figure 37 indicates the processes included in this study.

Transportation of the raw material from the raw material extraction and refinement to production of components is not considered in the study. LIFE chair components are supplied from internationally located suppliers as well as New Zealand based suppliers hence the geographical boundaries include: USA, Germany, China, New Zealand and Australia. With respect to time boundaries, data was gathered from suppliers commencing from 2005. The latest version of the EcoInvent v1.3 database (Frischknecht et al. 2005), was used on all other occasions.

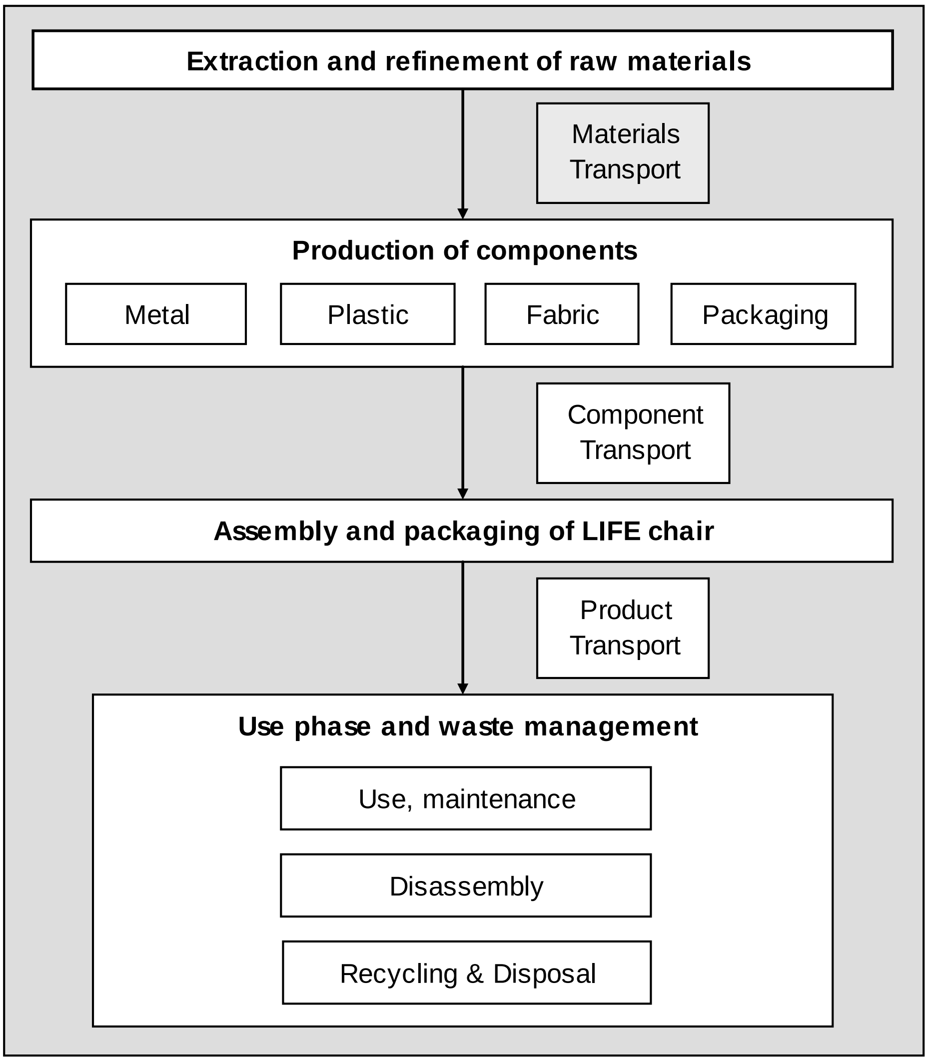

Figure 37: Life cycle processes of LIFE

FUNCTIONAL UNIT

The function of the LIFE chair is to provide stable, ergonomic, seating support for an office workstation. The functional unit for one LIFE chair was defined as provision of comfortable office seating, with the features stated in the product description, over a period of 10 years in line with the product warranty.

DATA QUALITY

The study uses two sources of data for the LCA:

1. Data from suppliers; and
2. Data from SimaPro7 databases, specifically the EcoInvent unit processes.

Data records were created using data from supplier processes according to the location of production. Where data from suppliers were unavailable the EcoInvent database was used. In cases were data were unavailable in the EcoInvent database, others such as IDEMAT 2001 were used where applicable. Some support materials to capital goods and manufacturing processes have been included as available in SimaPro7 (PRé Consultants, 2006). If possible, data for the relevant time periods were also chosen. The RA uses information from literature and from in house discussions.

ASSUMPTIONS

The main inventory assumptions were:

- Aluminium with the world average recycled content of 34% (Bertram 2006) was used for both the aluminium and GFN base chairs.
- An average recycled content of 20% for steel components was used in both chairs (with validation from suppliers).
- Polyethylene terephthalate, which was used as a proxy for Hytrel-crastin, is expected to display similar environmental effects as Hytrel-crastin.
- The customer was considered to be in Sydney, Australia, as this would represent an average-case scenario for transport.

6.2.2 INVENTORY ANALYSIS

Extraction and Production of Raw Materials

The extraction of raw materials and subsequent refinement were included for all materials considered in this study. However, almost all datasets in EcoInvent were compiled for use in a European context. In reality, the extraction and refinement of raw materials occur in places where respective components are manufactured (e.g. in China, USA, Australia and New Zealand). The study takes this geographical difference into account by substituting respective electrical energy models (Chinese, American, Australian and New Zealand) for all processed using European energy models. This modification is considered sufficient as process methodology for extraction and refinement of raw materials are likely to be uniform. The origin of raw materials is given in Table 17. The material datasets used are described in Table 18 and 19. These records were modified to reflect energy used in the respective location of manufacture.

Table 17: Origin of raw materials for components

Material	Location of component manufacture
Aluminium	Al base model: 58% USA/ 41% China/ 1% NZ FN base model: 72% USA/ 27% China/ 1% NZ
GFN	Al base model: 100% USA GFN base model: 43% USA / 57% Australia
Mesh/fabric	100% Germany
Steel	8% NZ/ 92% China
Hytrel-crastin	100% NZ
Other plastics	5% NZ/ 95% USA

Table 18: Materials in LIFE

Material	Dataset used in study
Aluminium	Aluminium, primary, at plant RER U from EcoInvent
	Aluminium, secondary, from old scrap RER U from EcoInvent
Steel	Steel, converter, unalloyed, at plant RER U from EcoInvent
	Steel, electric, un- and low-alloyed, at plant RER U from EcoInvent
Mesh/fabric	Polyester fabric I from IDEMAT 2001
Plastics	See Table 19

RER is the code given to represent the market situation in Europe, i.e. the data originates from Europe.

Table 19: Plastics in LIFE LCA

Plastic Category	Plastic	Dataset used in study
Thermoplasts	Nylon	Nylon 6, at plant/RER U from EcoInvent
	GFN	Nylon 6, glass-filled, at plant/RER U from EcoInvent
	PP	Polypropylene, granulate, at plant/RER U from EcoInvent
	Acetal	Polycarbonate, at plant/RER U from EcoInvent
	GFPP	PP GF30 1 from IDEMAT 2001
	PBT (Hytrel-crastin)	Polyethylene terephthalate, granulate, amorphous, at plant/RER U from EcoInvent
Thermosets	PU rigid	Polyurethane, rigid foam, at plant/ RER U from EcoInvent
	PU flexible	Polyurethane, flexible foam, at plant/RER U from EcoInvent
Rubber	ABS	Acrylonitrile-butadiene-styrene, ABS, at plant/RER U from EcoInvent

A brief explanation of the materials used in this study follows.

Aluminium

According to Bertram (2006) the global proportion of recycled aluminium (referred to as recycling input rate) for 2004 was 34%. Hence for the baseline study, it was assumed that the Al used in the chair was 34% recycled and 67% virgin. The input on the results of using 0% and 100% virgin aluminium was investigated as sensitivity analysis (Section 4).

The data used in the LCA study consist of the following records:

- For the production of virgin aluminium components, the data record from the EcoInvent unit process database for the production of primary aluminium in Europe was used;
- For the production of secondary aluminium, the data record from the EcoInvent unit process database for the production of secondary aluminium from old scrap in Europe was used; and
- For the production of 34% recycled aluminium components, both the records for primary and secondary aluminium production was used proportionately.

The comparison of impacts, specifically for Global Warming Potential (GWP) for the manufacture of the respective aluminium (100% recycled, 34% recycled and virgin) per 1kg of material are given Figure 38. This shows that 34% recycled aluminium contributes approximately 5 times more (540%) impact than 100% recycled aluminium, and virgin aluminium contributes 43% more impact than 34% recycled aluminium.

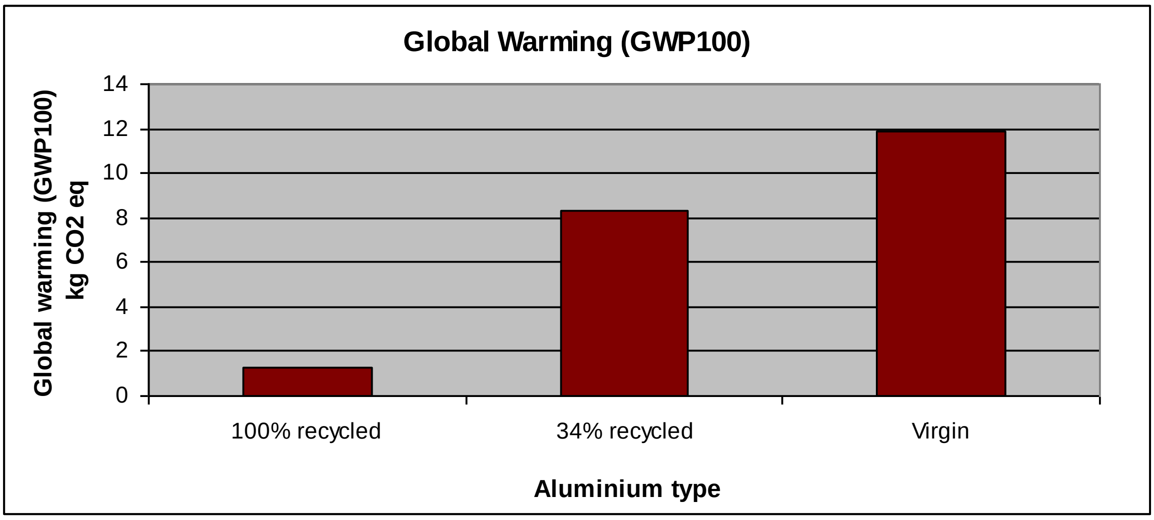

Figure 38: Global warming potential for aluminium with different recycled contents

Steel

Steel data used for Formway products come from the Ecoinvent unit process library. From the suppliers, it was found that an average of 20% recycled content was used in the steel used. Thus a data record was created using following records:

- Steel, converter, unalloyed, at plant; used to make primary steel (0.8kg);
- Steel, electric, un- and low-alloyed, at plant; used to make secondary steel (0.2kg); and
- Hot rolling, steel (1kg).

The record is essentially a modified version of the existing 'steel, low-alloyed, at plant' record found in the EcoInvent unit processes.

Plastics

All plastics data were taken from the existing records in the SimaPro7 databases (EcoInvent). The plastics considered in this LCA are given in Table 19.

Thermoplasts

Glass Filled Nylon

The existing EcoInvent unit process data record for glass filled nylon 6 was used in the study. This data record includes aggregated processes from raw material extraction to delivery at plant.

Hytrel crastin – TEEE +Polybutylene terephthalate (PBT)

No life cycle data for Hytrel crastin was available. Therefore the data record for polyethylene teraphthalate, granulate, amorphous, (PET) available in the EcoInvent unit process database was used as a proxy. This record represents an LCA data for production of amorphous PET from the European plastics industry.

Polypropylene (PP)

The existing data record for PP component production processes ranging from raw material extraction to polymerisation of propylene is considered in this record. The record is taken from the EcoInvent unit processes, which use data from the European plastics industry.

Acetal (POM)

There is no existing record for acetal and not enough data was available to create an accurate representation for this material. Thus polycarbonate was used as a proxy for POM. The data record used includes the polycarbonate granulate record found in the EcoInvent unit process.

Thermosets

PUR Foam and PUR rigid

There are two types of foam used in the LIFE chair; one for the seat cushion (flexible foam) and the other for arm pads (rigid foam). Formway manufactures the flexible foam in-house while the rigid foam comes preassembled as the chair arms. Out of the 820grams of total PUR, 140grams is the rigid foam, and the remaining 680grams is the flexible foam. The rigid PU is manufactured by a similar procedure as the flexible foam where the composition of the inputs is varied creating the different properties. The dataset used for the foams consist of the production and transportation of the monomers. The monomers for the production of flexible foam are transported to Formway where the flexible foam seat cushions are manufactured. The data record for polyurethane, flexible foam and polyurethane, rigid foam from the EcoInvent unit processes is used for the flexible and rigid foam respectively. The process uses no electricity (reactive process) hence no changes to the manufacturing record is made. The manufacture of the respective foams are carried out in Sub-system 1, therefore there is no other processing required in production of components.

Production of Components by Formway Suppliers

Formway's suppliers manufacture the LIFE chair's components according to Formway design criteria. Table 20 gives the main processes by which LIFE components are manufactured by the suppliers. The energy models used for production of components correlate to the geographical location given in Table 17. The original datasets that were modified are given in Table 21.

Table 20: Processing of LIFE materials

Material	Process	Dataset used in study
Aluminium	Die-casting	Information from suppliers
	Powder coating	Powder coating, aluminium sheet/ RER U from EcoInvent
Steel	Machined	Information from suppliers
Polypropylene	Injection moulding	Injection moulding /RER U from EcoInvent
Nylon	Injection moulding	Injection moulding /RER U from EcoInvent
Acetal	Injection moulding	Injection moulding /RER U from EcoInvent
ABS	Blow moulding	Blow moulding/RER U from EcoInvent
Back suspension fabric	Extruded polyester filament	Polyester fabric 1 from IDEMAT 2001
Glass filled polypropylene	Injection moulding	Injection moulding /RER U from EcoInvent

The process inventory datasets were taken directly from available databases available in SimaPro7 and were modified with respect to data gathered from suppliers. These modifications also reflect energy use in the respective geographical locations. For example, most New Zealand suppliers who manufactured components in New Zealand utilise electrical energy sourced from the grid. As opposed to some European countries and the US, New Zealand has lower electricity generation from fossil fuels and has no nuclear component; instead, it has a high renewable source content (up to 71% in 2004 (MED, 2006)). The following consists of a brief background as well as clarification on the use of data for the processes included in the LCA.

<u>Aluminium Die Casting</u>

Die casting is the process by which metal components are produced by forcing molten metal into dies at high pressure. There is no existing die casting data record in the databases. Thus the data record for casting bronze available in the EcoInvent database was modified with respect to information from suppliers as follows.

For the production of 1kg of die casted aluminium:

Table 21: Aluminium supplier input

Inputs	Quantity
Aluminium casting plant	1
Water for cooling	0.005m3
Electricity	4.52kWh
Heat – natural gas at industrial furnace > 100kW/RER	18 MJ
Outputs to air	
Heat waste	0.072MJ
Carbon monoxide	0.0624kg
NMVOC, unspecified origin	0.00133kg
Nitrogen oxides	0.00389
Outputs to water	
Aluminium	1.2E-8 kg
Hydrocarbons, unspecified	6.16E -8 kg
Suspended solids, unspecified	0.000347

Aluminium powder coating

Powder coating was carried out on the back casting of the LIFE chair as a precaution against corrosion. A surface area of 0.134m^2 is powder coated for both chair models. The EcoInvent data record for powder coating was used with modification for electricity reflecting the New Zealand case.

Steel Machining

The machining in the study includes steel cutting as well as some extruding (formation of gas cylinder tube) and welding. Steel components also comprise of small parts such as nuts and bolts that are simply considered as castings. The data record for machining steel is a modified version of the steel MIG welding record where electricity values were included according to suppliers in addition to existing electricity in the record (welding +cutting).

Steel information from suppliers is given below. Note that supplier 1 has combined all electricity for processing including that used for the manufacture of steel. Therefore, since the record cannot be separated into manufacturing steel and processing of manufactured steel for component production, this record was not used to calculate the average electricity used in machining steel. The only usable values for electricity come from the suppliers given in Table 22 and these are particularly for cutting steel into required lengths as well as some welding.

Table 22: Steel supplier input

Input materials	Supplier 1	Supplier 2
Scrap Steel	0.11kg/ kg of product	0.1kg/ kg of product
Electricity	0.34 kWh/ kg of product	0.55kWh/ kg of product
Outputs		
Unspecific wastes	0.13 kg/ kg of product	-

While there are a number of other steel suppliers, they did not have quantitative data on their processes. Thus taking the average of electrical energy used for processing (cutting) by suppliers 1 and 2, the electricity input is considered as approximately 0.444kWh per kg. This is in addition to the electricity requirement for welding.

Plastic Injection Moulding

Injection moulding of the various plastics used in the chair are assumed to follow the same procedure as that highlighted by injection moulding records in the respective EcoInvent dataset. These records reflect the world average hence deemed appropriate for this LCA.

Reactive Injection Moulding

Reactive injection moulding is used to manufacture both flexible and rigid foams. The processing data records given under polyurethane manufacture in the EcoInvent database was used respectively.

Extruded polyester filament

Since the production of nylon fabric was unavailable, the data record for the production polyester fabric was used as a proxy. This record is taken from the IDEMAT 2001 project, as textile data was unavailable in the EcoInvent database (Franklin Associates, 1993 and PWMI report 8). The US electricity data used in the set were modified to reflect the German electricity model as the fabric is manufactured in Germany.

Transportation of Components to Formway

Transportation of components includes transportation from Formway suppliers located in the USA, China, Australia, Germany and New Zealand to Formway Furniture assembling plant located in Wellington, New Zealand. In this case some of the distances given directly by the suppliers were considered. Calculation of distances using the shortest and most obvious transportation route was determined where supplier data did not exist. This included distance from supplier to nearest port, where overseas manufacturing was considered, followed by oceanic transport to New Zealand's Port of Wellington and subsequently road transport to the assembling plant at Gracefield Road, Wellington. The transport modes and distances considered in the study are given inTable 23. The proportion of components from each country is given in Table 17.

Table 23: Transport 1: Modes and distances from suppliers to Formway

Material	Location	Road (km)	Sea (km)
Aluminium	USA	17.3	10742
	China	45.3	8953
	New Zealand	190	-
GFN	Australia	35.3	1490
Fabric	Germany	429.3	11585
Steel	China	200	10050
	New Zealand	650	-
PBT	New Zealand	190	-
Other plastics	New Zealand	190	-
	USA	578	18761
Cables	USA	131.3	10176

The steel from New Zealand comprise of nuts, bolts, bushes, springs, etc. and these components are sourced from various parts of the world and due to constant changes in suppliers are virtually impossible to pinpoint exact origin. Thus the location of Formway's direct supplier in Auckland is included. Transport of components by road from supplier to Formway was considered to have been undertaken in 32-ton trucks as available in the EcoInvent database. Container ships were considered for sea transport as appropriate.

<u>Manufacture and Assembly of LIFE</u>

There are two distinct manufacturing steps in the manufacture of LIFE. The first involves the manufacture of the seat cushions and arms. This consists of water blown polyurethane manufacture. The reactive injection moulding data for manufacturing polyurethane foam from the EcoInvent database was utilised. The second is the assembly of metal and plastic components using hand and power tools, which only requires electrical energy and manpower. Calculations by production staff showed that the total electrical energy required to assemble the chair is approximately 6.8kWh.

The packaging for the two chairs consists of the manufacture of the packaging material as well as transport from supplier to Gracefield. The records used for the manufacture of packaging are given in Table 24.

Table 24: Data used for packaging

Packaging	Dataset used
Cardboard	Corrugated board, mixed fibre, single wall, at plant/ RER U
Film	Packaging film, LDPE, at plant/RER U

The packaging material is transported from a supplier based 6 km away from Gracefield. Thus the NZ electricity model for the manufacture of packaging materials has been substituted.

Transport from Formway to Consumer

Formway transports its LIFE chair to New Zealand and Australian consumers. For this study, it is assumed that the finished products are transported to the Wellington Port prior to being shipped to Sydney, Australia. The distances and modes of transport are given in Table 25. Transoceanic freight ship transports the product to the Port of Sydney where it is then transported to Formway's Rockdale plant and subsequently, to Central Sydney where Formway's showroom is located. 16t lorries given by EcoInvent unit processes were considered for all road transport while transoceanic freight ships were considered for sea (as given by EcoInvent unit processes).

Table 25: Distance and mode of transport to customer

Location	Mode of transport	Distances (km)
Gracefield plant to Port of Wellington	Road	15.3
Port of Wellington to Port of Sydney	Sea	1236
Port of Sydney to Rockdale plant	Road	17.2
Rockdale plant to Sydney showroom	Road	16.3

Use and Waste Management of LIFE chair

No environmental exchange takes place during the use of the product, i.e. the chairs do not require energy or water to function, and there are no emissions made during use. It is assumed that no repairs are made during the 10 year period defined in the functional unit of the chair. The only foreseeable need is the need for cleaning. Wiping the surface to clear dust or any marks made constitutes the cleaning procedure, which will have minimal environmental consequences.

At end of life, it is most likely that the LIFE chair will be reused as a second-hand product until such time that it is disassembled with certain components being reused and recycled. For this study, three scenarios were investigated as follows:

1. Baseline scenario: The entire chair is landfilled;
2. Metal scenario: All metals are considered recycled (accounting for 68.4% of the LIFE chair with aluminium base, and 59.4% of the LIFE chair with GFN base). The remaining material is considered un-recyclable and landfilled; and
3. Technical scenario: All metals and large plastic components are recycled. The large plastics include the back frame, trim ring, seat pan, GFN base for the GFN base chair, foam cushion. Thus approximately 81.8 % of the LIFE chair with aluminium base and 82.6% of the LIFE chair with GFN base are recycled. The technical scenario involves sending selected components to the nearest recycler, who transports it to a recycler located within the country, or overseas.

Transport to end of life treatment facilities

The following distances to landfilling or recycling facilities are considered in the study. These correlate to the nearest and most practical destinations for components at end of life.

- Transport to landfill from the Sydney showroom to Horsley Park Waste Management Facility: 42km. The entire chair or parts are transported in small (16t) lorries.
- Transport to disassembling and recycling facilities:
    - Aluminium components are sent to Sims Metal recyclers, NSW (31.5km) who then transport the material to their smelter in Geelong, VIC (910km) where it is melted, alloyed and cast into ingots, ready for use by manufacturers. Transportation is carried out in 32t lorries;
    - Steel components are also sent to Sims Metal recyclers, NSW (31.5km) who then send it to OneSteel Whyalla Steelworks where it is added to the feed (1709km). Transport is carried out in 32t lorries;
    - Plastics (GFN: base and back frame; Hytrel: seat) sent to Plastic Recyclers Australia in Port Pirie, SA (1579km). Transportation of material is in small (16t) lorries; and
    - Packaging is sent to Visy Recycling in St. Peters, NSW (7.2km), in 16-ton lorries.

Assumptions for the transport at end of life are as follows:

- The waste management scenarios are purely hypothetical since the LIFE chairs have not yet reached end of life there is yet no practical program in place to cater to waste management. However, the values given depict the most possible strategy for material recycling and transport;
- Transportation of components to distances less than 100km are carried out in small Lorries whereas transportation for long distances is carried out in 32t lorries; and
- Transportation of selected material for recycling is carried out separately from the material for landfill. The components for landfill are transported all together while those for recycling have different paths and hence different distances.

Modelling the recycling scenarios

In terms of aluminium, three separate scenarios for recycling were modelled in order to represent a more accurate case for recycling the respective LIFE chair models. The available data record in EcoInvent considers the output of recycling as avoidable impact. Thus the scenarios have been modelled such that:

- For primary (virgin) aluminium – recycling will essentially avoid the production of primary aluminium
- For 34% recycled aluminium – recycling will essentially avoid the production of 66% primary and 34% secondary aluminium
- For 100% recycled aluminium – recycling will essentially avoid the production of secondary aluminium.

Due to the avoided impacts, all three recycling scenarios give net negative values when modelled. This is due to the avoided impact as per above scenarios (Figure 39).

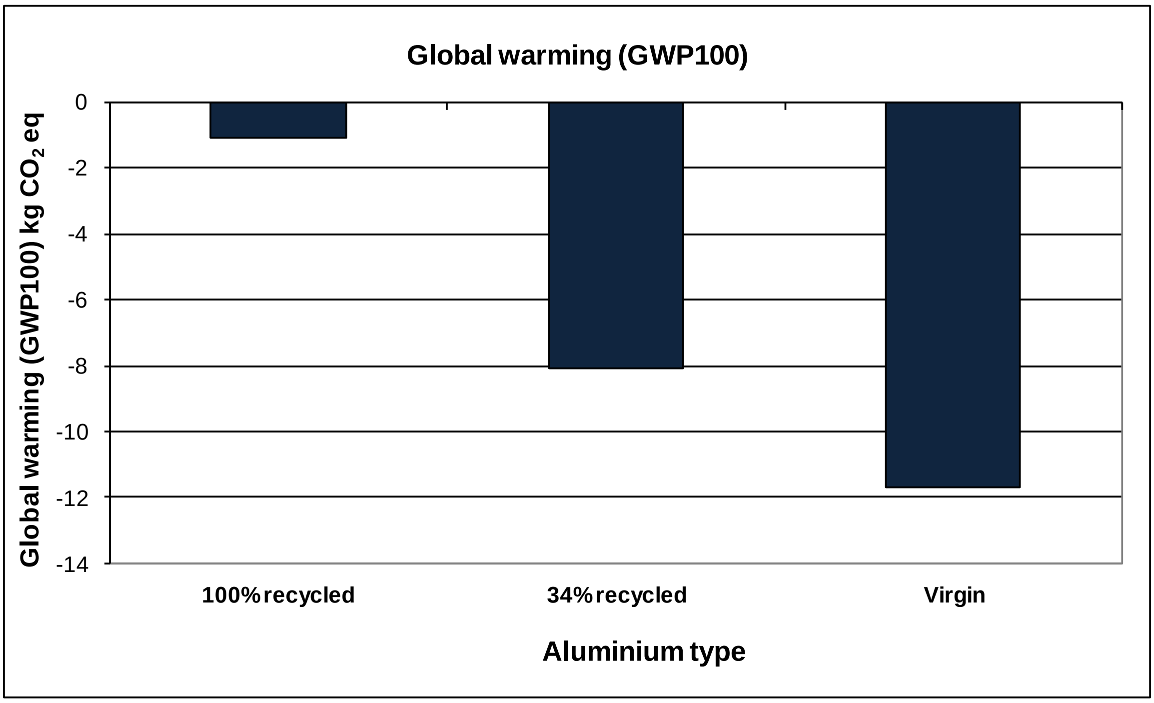

Figure 39: Global warming potential for recycling aluminium

Steel

The steel components are also recycled to avoid the respective inputs, i.e. Steel consists of 20% recycled content; hence recycling will essentially avoid the production of 80% primary and 20% secondary steel.

Plastic

Recycling is carried out to avoid mixed plastic granulates.

Modelling Energy

Formway's LIFE chair is manufactured using components that are made by numerous suppliers located around the world. Thus the electrical energy mixes used in processing of raw materials (making the most likely assumption that the raw materials are also found in the location of component manufacture) as well as the manufacture of components depends on where components are manufactured. The electrical energy data given in the database processes (EcoInvent, IDEMAT 2001, BUWAL250, etc.) are primarily based on European electricity data. In order to establish a realistic scenario for the LCA, existing European energy data for processing, at both the raw materials and component production stages, is substituted by the electrical energy data per country of origin as given in Table 17. This is expected to make the study Formway-case specific.

Electricity New Zealand

Since the assembly of components to form the LIFE chair is carried out in New Zealand, the following representation of the New Zealand electricity mix will be used.

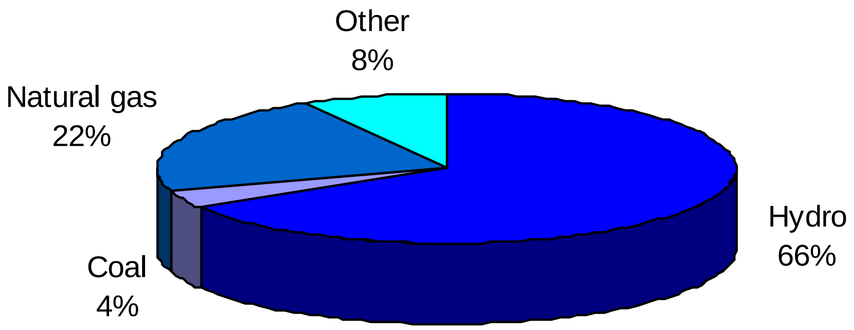

Figure 40: New Zealand electricity composition used in the LCA (MED, 2006)

However, due to the unavailability of data for geothermal and other electricity types, the New Zealand data record is composed assuming that a total of 92kWh is produced. This is broken down as follows:

- Electricity from hydropower: 66kWh;
- Electricity from gas: 22kWh; and
- Electricity from coal: 4kWh.

8% of the electricity make up for this scenario has been neglected and this is a considerable limitation.

Electricity U.S.A.

The energy record for U.S. electricity production in 2003 (EIA, 2004) was made up of the following composition given in Figure 41. In this case, a total of 97kWh, which comprises of 51kWh electricity from coal, 16kWh electricity from natural gas, 3kWh from petroleum, 20kWh from nuclear and 7kWh from hydropower was considered. All other sources of electricity were ignored for this study. The main method of dealing with the electricity used in the production of raw materials and the subsequent processing involves substituting new energy model in for each and every unit process found along the processes. This means that all electricity values must be traced to their origins for every process and changed accordingly.

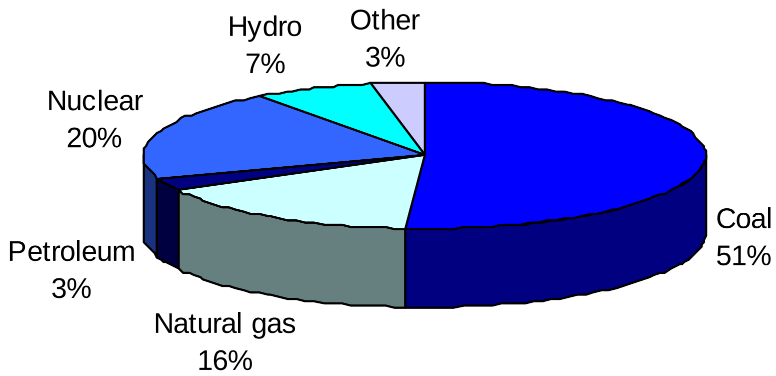

Figure 41: U.S.A electricity composition (EPA, 2005)

Figure 42 shows the impact contribution from the production of electricity for Australia (ESAA, 2005), New Zealand (MED,2006), USA (EIA, 2005a) and China (EIA, 2005b). The results indicate that higher fossil fuel use, specifically coal, leads to higher total impact. Thus electricity production for Australia, China and USA exhibit the highest impact contributions. New Zealand, which makes use of approximately 65% hydro, has the least impact contribution.

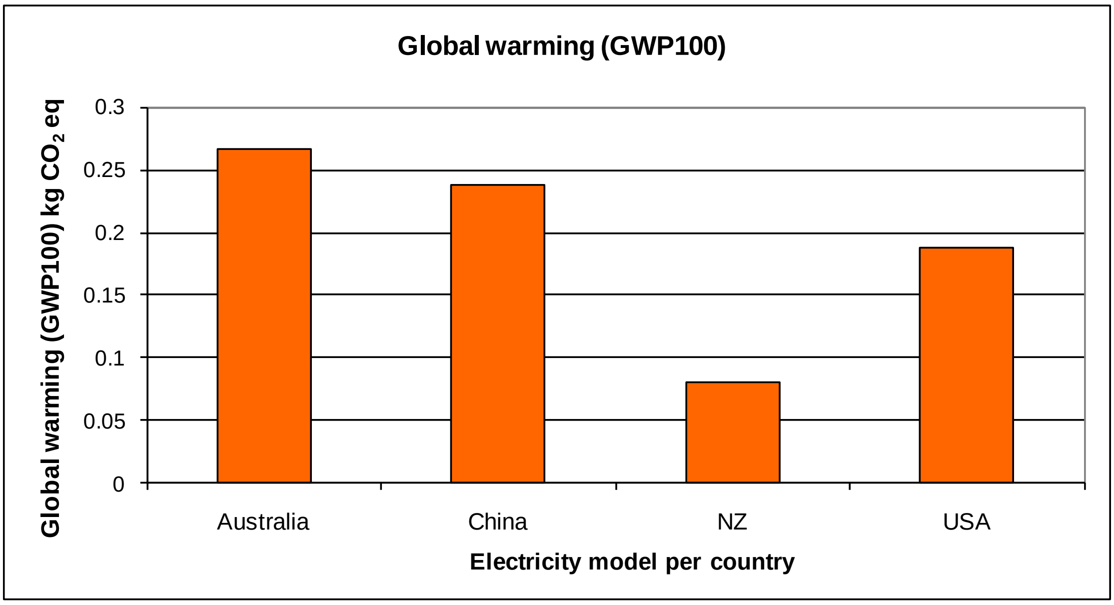

Figure 42: Comparison of global warming potential for electricity models per country

6.2.3 IMPACT ASSESSMENT

Leiden University's Institute for Environmental Sciences developed CML 2 baseline 2000 (Guinée et al. 2000), which is the impact assessment methodology used in this study. CML 2 baseline 2000 is the successor of CML 1992. The overall result of the impact assessment is presented graphically in Figure 43. The characterisation results for Global Warming Potential (GWP100) are also presented separately (Figure 44 shows the global warming potential of the different stages of the life cycle; Figure 45 shows the global warming impact at the most impact contributing stage of the lifecycle – the extraction and refinement of raw material; Figure 46 showing impacts from the waste management scenario at end of life; and Figure 47 showing results of the sensitivity analysis with deferent aluminium types containing three different recycling contents). The global warming (GWP100) category was chosen as the main impact category with which to illustrate the results for two reasons:

1. Global warming is a significant issue for businesses and the environment; and
2. Other categories follow a similar pattern of results as the GWP100 category.

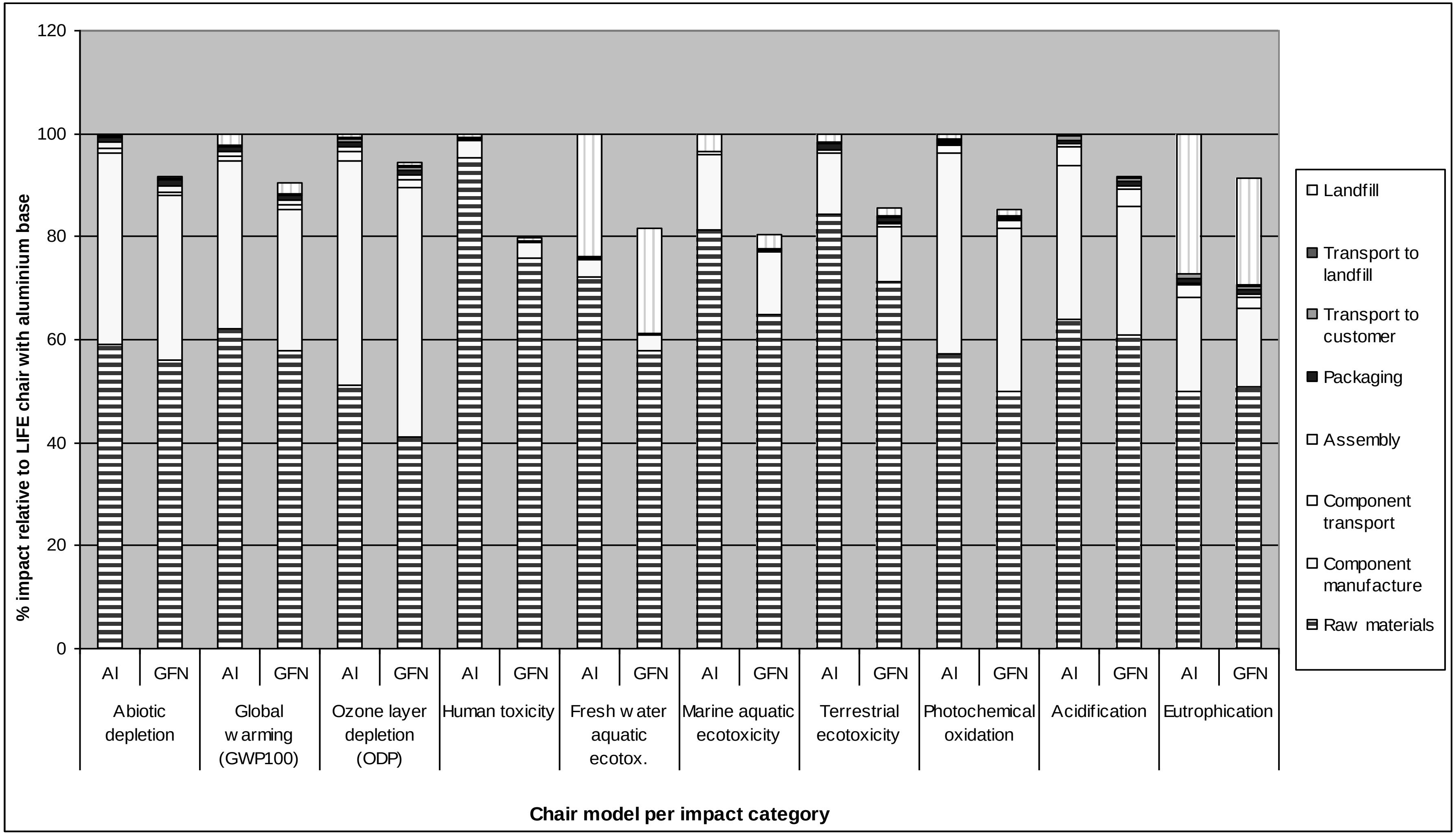

Figure 43: % impact comparison of the two LIFE chair models using default categories relative to each impact category of the chair model with aluminium base

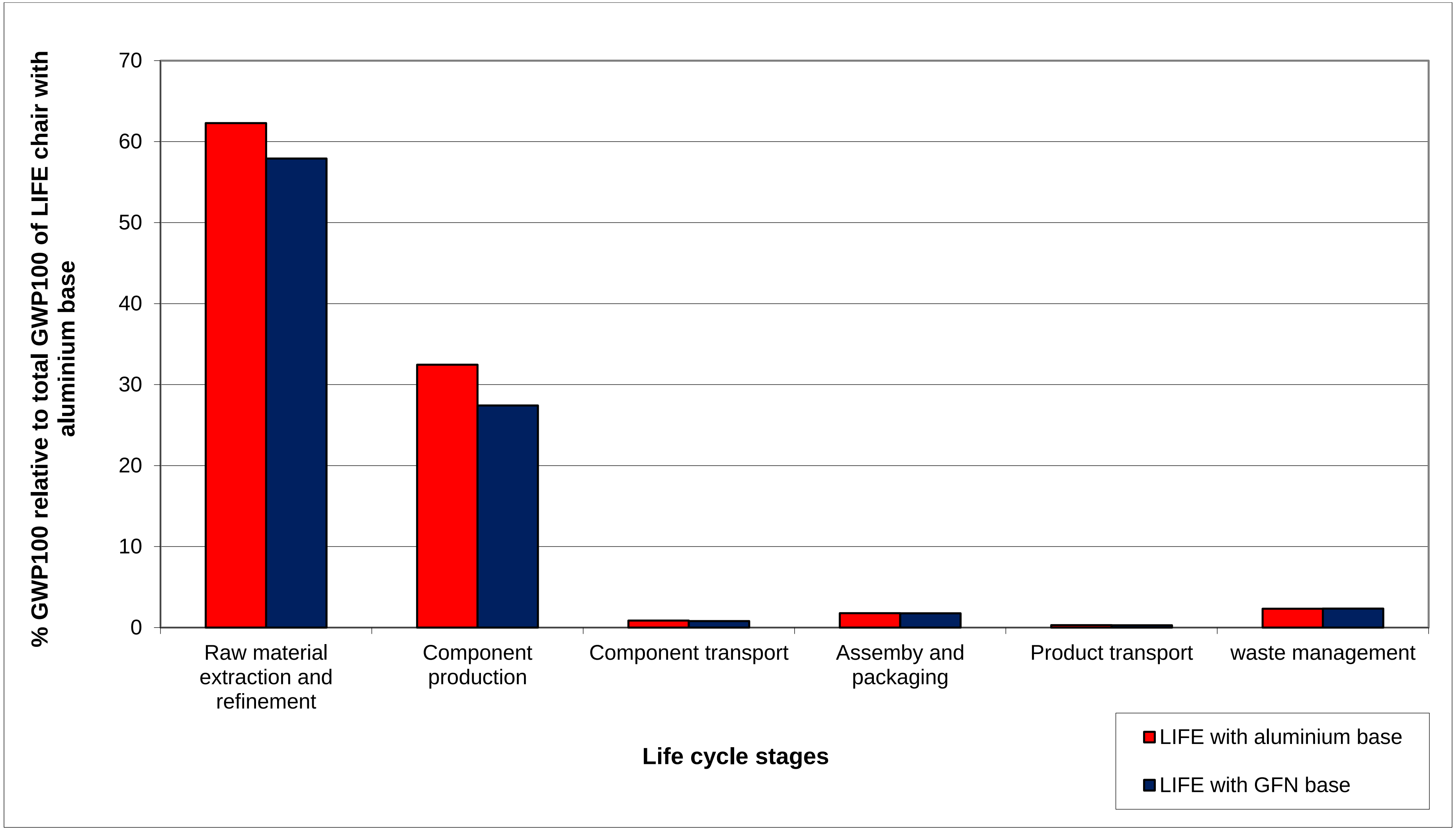

Figure 44: %GWP100 results for the life cycle stages of the two LIFE chair models

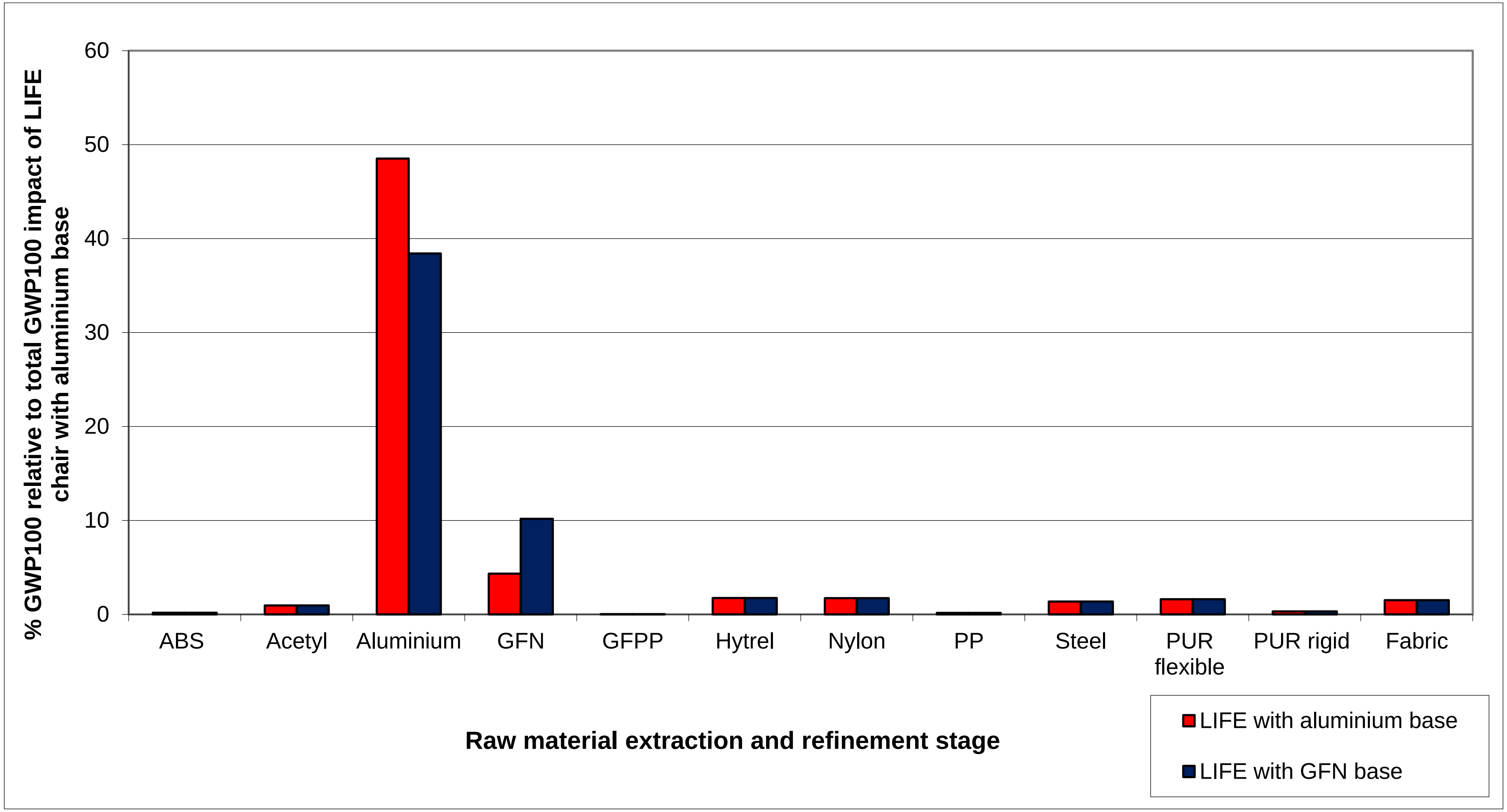

Figure 45: %GWP100 results from raw material extraction and refinement stage

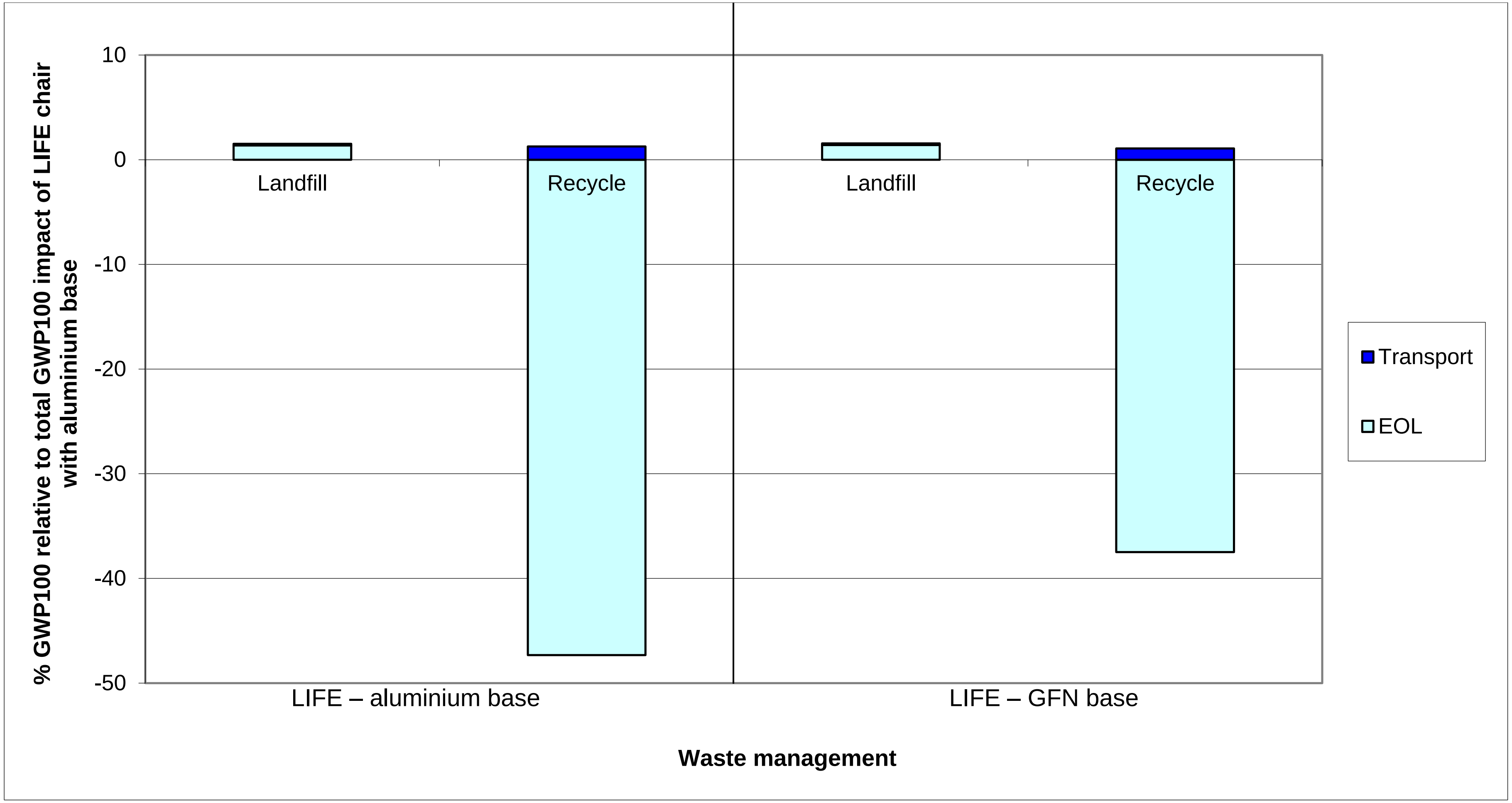

Figure 46: %GWP100 results from waste management stage considering landfill versus recycling

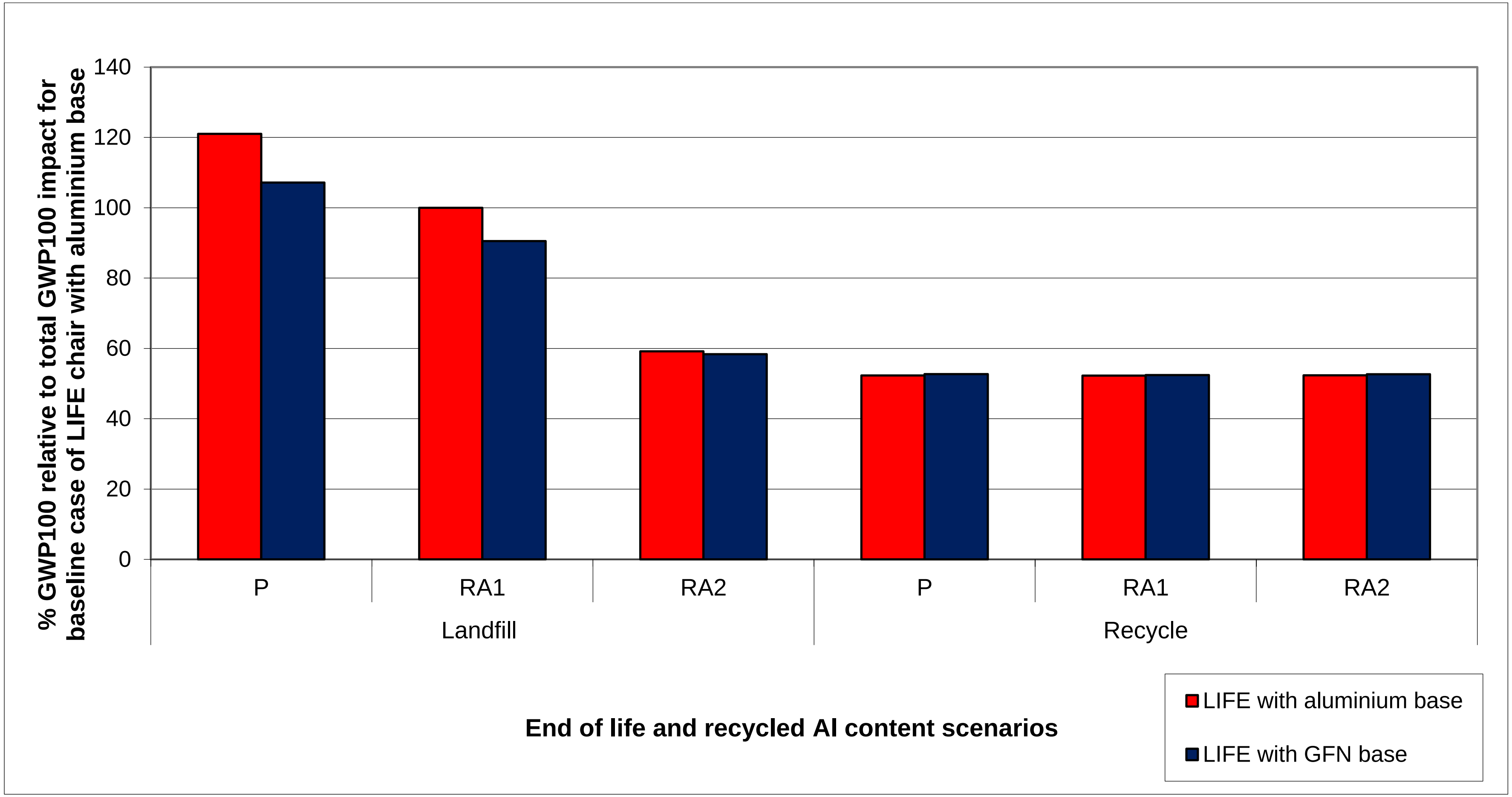

Figure 47: %Impact of different aluminium recycled content on the total life cycle of the two chair models

Figure 44 shows that the most global warming impact is produced at the raw material extraction and refinement stage of the lifecycle. Figure 45 narrows down the components that lead to the high global warming impact potential at the raw material extraction and refinement stage and thus highlighting aluminium as a major source of risk to the product system. Figure 46 and Figure 47 show end of life impacts for recycling and landfilling and how the content of recycled aluminium in the product affects the overall impact which may be significant in treating the risks from aluminium. The case study results for the product system are given separately as LCA results (published as Babarenda Gamage et al. (2008)) and RA results (similar to the results found in Babarenda Gamage and Boyle (2008)).

THE LCA STEP

As mentioned in the last two chapters, the LCA step is to determine the lifecycle inventory of the product system. It also helps to streamline the study by allowing the practitioner to concentrate on specific impact categories that are deemed significant for the current global outlook. The first set of results given in Chapter 6 is for the baseline case, which includes all the life cycle stages using the average aluminium recycled content (34%) and considering landfill for the waste management scenario. The remaining results are presented according to the three goals outlined within the LCA steps of the model. The GWP100 results are presented as a percentage relative to the total GWP100 of the LIFE chair model with the aluminium base. Figure 43 showing the nine default impact categories as per CML 2 for the baseline case. This figure mostly shows that the impacts are largely distributed in the raw material extraction and refining phase of the product life cycle for almost all the impact categories.

<u>Results for goal 1: Determine hotspots in the lifecycle</u>

Figure 44 illustrates the individual contribution from each life cycle stage of the two LIFE chair models. This shows that the raw material extraction and refinement and component production stages contribute to high GWP100. However, the raw material extraction and refinement stage is of most significance, contributing over half of the total GWP100 impact for both LIFE chair models. The two transport stages and the waste management stage show negligible GWP100 contribution in comparison. Since the raw material extraction and refinement stage was the most significant life cycle stage, it was investigated further to determine the material responsible for this impact contribution as shown in Figure 45. This figure compares the percentage GWP100 results contributed from the raw material extraction and refinement stage relative to the total GWP100 impact of the LIFE chair model with the aluminium base.

It was found that aluminium was the major contributor to the GWP100 impact. For the LIFE chair model with the aluminium base, aluminium was found to be responsible for approximately 78% of the GWP100 impact at the raw material extraction and refinement stage. Aluminium contributes to 59% and 50% of the total weight of the LIFE chair models and it also has relatively high energy requirement to produce, therefore it is not surprising that environmental impact from aluminium dominates the raw material and refinement stage.

Results for goal 2: Comparison of LIFE chair models

Figure 43 to Figure 47 also contain the comparison of GWP100 for the two LIFE chair models. According to the results, the LIFE chair model with the aluminium base contributed approximately 10% more GWP100 than the GFN base model for the entire life cycle. Since the main difference between the two chair models is the content of aluminium and GFN, the main difference between the two chair models for the raw materials extraction and refinement stage is also the impacts contributed by aluminium and GFN (Figure 45). Given that the chair model with the aluminium base has more aluminium in its material composition, the GWP100 contribution from aluminium is higher than that of the GFN base model. Likewise, since the chair model with the GFN base has more GFN, GWP100 contribution from GFN is greater for this model during the raw material extraction and refinement stage. Hence the results directly reflect the difference in the two material contents of the respective chairs.

Results for goal 3: Waste management

With respect to waste management, both chairs are technically over 90% recyclable; however, this study compares the two scenarios where: 1) The entire chair (including packaging) is landfilled; and 2) All metal components are recycled and the remainder landfill. The transport of components to the nearest landfill/recycling facility is also included. The results from the comparison of EOL processes and transport to the EOL facilities are given in Figure 46. This figure compares the percentage GWP100 from transport and EOL scenario for the two LIFE chair models relative to the total life cycle GWP100 impact of the LIFE chair model with the aluminium base.

The results indicate that landfilling both LIFE chair models result in very similar GWP100 impact. The recycling scenario however, results in avoided impact, which is depicted by negative figures. This avoided impact can be thought of as the avoided burdens from recycling materials in relation to the production of raw materials. Since there is more metal in the chair model with the aluminium base, it has more avoided impact. With regard to recycling, the benefits of recycling both models clearly outweigh the impact generated from transport to recycling facilities.

With respect to goal 2, the difference between the total GWP100 for the entire life cycle of the two LIFE chair models was found to be approximately 10%, where the chair model with the aluminium base contributed to the higher impact. When the two models are recycled, there is negligible difference between them. Thus the investigation of the waste management options indicate that recycling at EOL is fundamental in reducing GWP100 impact.

Sensitivity analysis

Sensitivity analysis was carried out to determine the relative effect of recycled aluminium content, since aluminium is a major contributor of GWP100 in the study. Three scenarios were considered:

- Primary aluminium use (P);
- 34% recycled aluminium – baseline case (RA1); and
- 100% recycled aluminium (RA2).

The total results considering the sum of all life cycle stages for both LIFE chair models are given in Figure 47. Note that this figure compares the percentage GWP100 relative to the total life cycle GWP100 from the baseline case (considering 34% recycled content in aluminium and landfilling at EOL) of the LIFE chair model with the aluminium base. The sensitivity analysis showed the significance of the recycled content in the most significant material in the product system where impact decreased with increased recycled content in the aluminiuim used. This essentially leads to a mitigation of risk later on.

6.2.4 RISK ASSESSMENT

The risk assessment phase results in two risk matrices. The first risk matrix is based on the risks from the product system to the overall complex system in which it functions. This is generated by identifying, analysing and evaluating risks associated with the impact categories as shown in Table 26. For this research simple risk matrices are used to illustrate the potential of the model. The matrices have been populated with qualitative risk data from literature as well as discussions and interviews with Formway staff. For more vigorous risk assessments, other risks methods given in Chapter 5 can be used with a larger stakeholder base. The temporal scale for this assessment is equivalent to those identified through discussion regarding risk planning by the company as given previously. Three separate matrixes may be formed per environmental, social and economic systems. These matrices can be integrated together to form a single matrix as discussed in the previous chapter. The result presented here consists of the integrated matrix. The risks are evaluated according to the matrix in Figure 48. While there are many possible actions to take with respect to risks, the actions for this study are defined as follows:

1. Accept: the risks may be accepted where no further actions are taken with respect to the risk event. The events may be reviewed in order to prevent their significance from being overlooked;
2. Control: The risks may be controlled where the events or their results are measured and tracked, where policies have been enacted to aid in the management of the risk events so that they do not become critical; and
3. Treat: The risks may be treated such that the impacts are actively transferred (insurance), mitigated or eliminated.

The probabilities and consequences are estimates according to literature and trends. Note that rather than the probability being considered as negligible in the case of uncertainty, a precautionary approach in considering it as "likely" is taken to allow the risk to be investigated further before considering it as acceptable and putting it aside.

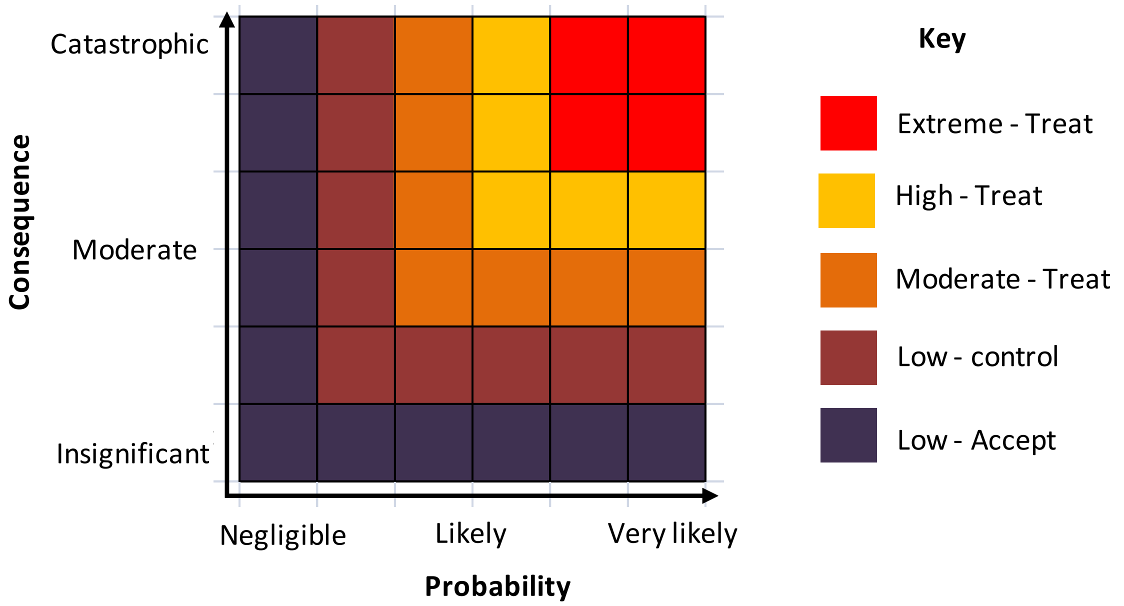

Figure 48: Risk matrix for evaluating risks

Table 26: Environmental, social and economic risk associated with impact categories associated with impact categories

		Temporal scale						
Impact Category	**Spatial scale**	**Short term**	**Medium term**	**Long term**	**Probability**	**Consequence**	**Level of risk**	**Notes/ References**
Abiotic depletion	Local	• Restrictions in supply of minerals, timber, fossil fuels • Increased resource costs • Inability to meet demand of goods and subsequent losses • Shut down of certain manufacturing facilities	• Research into new materials or sources of energy • Shortages of resources • Shut down of plants, obsolescence of products • Loss of jobs, income	• Extreme scarcity leading to reliance on other types of material and sources of energy • Mass unemployment • Social conflict over remaining materials	Likely	Moderate - catastrophic	High- Extreme - treat	Local businesses will be highly susceptible to local changes
	Regional				Likely	Moderate	Moderate - treat	
	Global				Likely	• Insignificant if the resource can be substituted for • Catastrophic if there are no substitutes	Low – high risk Either accept or treat.	Recycling, material substitutes may assist in mitigating risks
Ozone layer depletion (ODP)	Local	• Health risks	• Health risks	• Health risks • Escape of atmosphere into space • Ecosystem breakdown due to solar radiation exposure • Increasing regulatory pressure	Likely	Moderate to catastrophic	Moderate- high - treat	Local, regional and global area affected according to where the ozone is depleted
	Regional							
	Global							

<table>
<tr><th colspan="2"></th><th colspan="3">Temporal scale</th><th colspan="4"></th></tr>
<tr><th>Impact Category</th><th>Spatial scale</th><th>Short term</th><th>Medium term</th><th>Long term</th><th>Probability</th><th>Consequence</th><th>Level of risk</th><th>Notes/ References</th></tr>
<tr><td rowspan="3">Global warming (GWP100)</td><td>Local</td><td>• Impact from policy (carbon trading)
• Lifestyle changes
• Subsistent farming affected</td><td rowspan="2">• Impact from policy (carbon trading)
• Lifestyle changes
• Insurance costs
• Droughts
• Heat waves
• Floods
• Extreme weather events
• Subtle climate changes leading to changes in agriculture</td><td rowspan="3">Climate change:
• Sea level rise
• Unstable weather
• Expansion of desert
• Spread of disease and pests
• Environmental refugees
• Lifestyle changes
• Insurance costs
• Ecosystem breakdown
• Species extinction
• Severe droughts
• Severe floods
• Increasing regulatory pressure
• Habitat loss</td><td rowspan="3">Likely in the long term</td><td rowspan="3">Moderate to catastrophic</td><td rowspan="3">Moderate-high - treat</td><td rowspan="3">Information from IPCC reports: Schneider et al., 2007</td></tr>
<tr><td>Regional</td><td></td></tr>
<tr><td>Global</td><td></td><td>Slight changes</td></tr>
</table>

<table>
<tr><th rowspan="2">Impact Category</th><th rowspan="2">Spatial scale</th><th colspan="3">Temporal scale</th><th rowspan="2">Probability</th><th rowspan="2">Consequence</th><th rowspan="2">Level of risk</th><th rowspan="2">Notes/ References</th></tr>
<tr><th>Short term</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="3">Human toxicity</td><td>Local</td><td colspan="3" rowspan="3">• Health risks – cancer, chronic illness
• Poisoning and death
• Insurance costs</td><td rowspan="3">Negligible - likely</td><td rowspan="3">Moderate - Catastrophic</td><td rowspan="3">Low-High Control, treat</td><td rowspan="3">Environmental Risk Assessment (ERA) can be used to compare concentrations to determine effects of individual substances.</td></tr>
<tr><td>Regional</td></tr>
<tr><td>Global</td></tr>
<tr><td rowspan="3">Fresh water aquatic ecotoxicity</td><td>Local</td><td rowspan="3">• Health risk and death
• Fisheries affected by death of fish
• Water scarcity for domestic use
• Water scarcity for agricultural and industrial use</td><td rowspan="3">• Bioaccumulation of toxic substances in aquatic life, fish, etc.
• Disease related to toxic substance
• Hydrological cycles intensified
• Severe weather
• Change in salinity</td><td rowspan="3">Water scarcity</td><td rowspan="3">Negligible - likely</td><td rowspan="3">Catastrophic</td><td rowspan="3">Moderate – High Treat</td><td rowspan="3">Dispersion of toxic substances may dilute the effects however local effects would be significant</td></tr>
<tr><td>Regional</td></tr>
<tr><td>Global</td></tr>
<tr><td rowspan="3">Marine aquatic ecotoxicity</td><td>Local</td><td>• Health risk and death
• Fisheries affected by death of fish</td><td colspan="2" rowspan="3">• Bioaccumulation of toxic substances in marine life
• Health risk from ingesting contaminated marine produce
• Species extinction
• Coral bleach</td><td rowspan="3">Negligible - likely</td><td rowspan="3">Moderate - Catastrophic</td><td rowspan="3">Low-High Control, treat</td><td rowspan="3">Huijbregts et al. (2000a)
Huijbregts et al. (2000b)</td></tr>
<tr><td>Regional</td><td></td></tr>
<tr><td>Global</td><td></td></tr>
</table>

Impact Category	Spatial scale	Temporal scale			Probability	Consequence	Level of risk	Notes/ References
		Short term	Medium term	Long term				
Terrestrial ecotoxicity	Local	• Health risk and death via ingestion • Agricultural land affected	• Bioaccumulation of toxic substances in birds and animals • Health risk from ingesting contaminated produce • Species extinction • Contamination of water		Negligible - likely	Moderate - Catastrophic	Low-High Control and/or treat	Guinée et al. (2002) Huijbregts et al. (2000a) Huijbregts et al. (2000b)
	Regional							
	Global							
Photochemical oxidation	Local	• Respiratory ailments •	• Insurance risks • Tourism adversely affected • Health risks	• Chronic health risk - cancer • Health decline of population • Biodiversity affected	Likely (already an occurrence in major cities)	Moderate – Catastrophic (people with heart and lung conditions affected the most)	Moderate to High Requires treatment	Effects of photochemical oxidation would depend on the substance being oxidised.
	Regional							
	Global							

Impact Category	Spatial scale	Temporal scale: Short term	Temporal scale: Medium term	Temporal scale: Long term	Probability	Consequence	Level of risk	Notes/ References
Acidification	Local	• Acid rain affecting crops. • Damage to property, etc.	• Damage to property • Ecosystem breakdown (coral) • Acidification of water bodies • Acidification of soil affecting agriculture	• Ecosystem breakdown • Extinction of acid sensitive organisms • Damage to property • Changes in S and N cycles	Negligible - likely	Moderate - catastrophic	Low – moderate Either accept or treat	Bouwman et al., 2002
	Regional				Negligible - likely	Moderate		
	Global				Negligible - likely	Moderate		
Eutrophication	Local	• Fisheries affected by death of fish • Build-up of toxic substances • Food source for locals diminished • Increase in turbidity	• Algal bloom • Toxic build-up in rivers, lakes • Species invasion • Dying out of fish species • Decline in the amenity value of the water source • Change in taste or odour • Spread of pests	• Species invasion • Death of species • Decrease in biodiversity • Decrease in • Changes in S and N cycles • Increased sedimentation • Deepwater oxygen depletion • Aquatic macrophyte growth	Negligible - likely	Moderate - catastrophic	Low – moderate Either accept or treat	The issue is largely for industrialised or agricultural areas where the risks decrease away from the areas Bouwman et al., 2002
	Regional				Negligible - likely	Moderate		
	Global							

The second risk matrix (Table 27) is associated with the impact causing resources and processes in the product system. The risks given in the table are from literature as well as via discussion with staff. The highest impacts are caused at the extraction of materials and refinement. These impacts are from aluminium extraction where use of energy is one of the significant risk contributors. The other risks to the product system from resources in the product life cycle include the production of glass filled nylon, of which the use of fossil fuels as energy and raw material give rise to risk. If the risks from the resources are realized, chances are that the product system would be in jeopardy which in turn would have negative impact on the economic system reverberating through to the social system. Likewise, if there are social crisis in regions where suppliers are located, risk to the supply of resources increases and can negatively impact the product system as well as the economic system. The risks are analysed using the same risk matrix given in Figure 48. The spatial scale for the risk assessment is local, where the product system is located. The risks are subject to local, regional and global events with respect to the location of manufacture, processing, etc.

Table 27: Classification of generic risk to the LIFE product system from selected resources

	Risk per temporal scale				
Resource	**Short term (6months - 1 year)**	**Probability**	**Consequence**	**Level of risk**	**Notes/References**
Aluminium	Fluctuation in price effecting supply	Likely - Very likely	Moderate - catastrophic	High-Extreme Treat risk	SME's would be hardest hit
	Waste generation and disposal contaminating land, taking up space, etc.	Likely	Moderate	Moderate-High Treat risk	Depends on treatment before waste disposal
	Immediate health impacts of exposure to processing chemicals	Likely	Moderate	Moderate-High Treat risk	Depends on health and safety regulations and practice
	High energy requirement	Very likely	Moderate	Moderate-High Treat risk	The consequences will remain moderate as long as there is a steady source of energy
	Medium term (5 years)				
	Resource scarcity due to high demand	Likely	Moderate	Moderate-High Treat risk	Availability and technology to access and make use of scrap
	Long term health effects associated with processing	Likely	Moderate - catastrophic	Moderate -High Treat risk	
	Energy requirements affected by potential fossil fuel prices/depletion	Likely	Moderate	Moderate -High Treat risk	Depends on whether other sources of energy can be developed
	Increase in price due to actual or perceived scarcity	Likely	Moderate	Moderate -High Treat risk	
	Long term (Beyond 5 years up to 100 years)				
	Competitive pricing where rich countries monopolize on supply	Likely	Moderate - catastrophic	Moderate -High Treat risk	Depends on whether other materials can be used as substitute
	Local supply scarcity including scarcity due to intense demand	Likely	Moderate - catastrophic	Moderate-High Treat risk	Aggravated by population and competition
	Chronic accumulated health impacts	Likely	Moderate - catastrophic	Moderate -High Treat risk	Depends on individual's body, predisposition, etc.
	Energy requirements affected by potential fossil fuel prices/depletion	Likely	Moderate	Moderate -High Treat risk	

	Temporal scale				
Resource	**Short term (6months - 1 year)**	**Probability**	**Consequence**	**Level of risk**	**Notes/ References**
Fossil Fuel, Plastics	Emission regulation forcing less use of fuels	Negligible	Moderate	Low – Accept and control	Not likely to happen as long as economic growth and development is the target for mankind
	Cost due to fluctuations in global market	Likely	Moderate	Moderate -High Treat risk	Regnier, 2007; Sadorsky, 1999
	Health effects due to combustion	Likely	Moderate - catastrophic	Moderate -High Treat risk	Wilkinson et al., 2007; Dockery et al., 1993; Craig et al., 2008
	Employee health effects due to toxic/hazardous exposure (including during plastic manufacture)	Likely	Moderate - catastrophic	Moderate -High Treat risk	Gardner, 2003; Niven and McLeod R, 2009; Kirkeleit et al., 2008
	Medium term (5 years)				
	Impacts from greenhouse gas emissions leading to global warming	Very likely	Moderate - catastrophic	Moderate-extreme. Treat risk	Refer to Table 26
	Increase in price due to actual or perceived scarcity (e.g. war or increased demand)	Likely	Moderate	Moderate -High Treat risk	
	Long term health effects due to combustion	Likely	Moderate - catastrophic	Moderate -High Treat risk	Pope III et al., 2002; Davis, 1997
	High impact health effects from exposure (cancer)	Likely	catastrophic	Moderate -High Treat risk	Wilkinson et al., 2007; Dockery et al., 1993; Craig et al., 2008
	Regulation of selected plastic production	Negligible-Likely	Moderate	Low-moderate Accept or treat	Possible treatment is the substitution of material
	Increased dependency on coal	Likely	catastrophic	Moderate -High Treat risk	Probability depends on whether oil will run out and no other green source of energy is available
	Scarcity for source of plastic pellets to manufacture material	Likely	Moderate - catastrophic	Moderate -High Treat risk	

	Temporal scale				
Resource	**Short term (6months - 1 year)**	**Probability**	**Consequence**	**Level of risk**	**Notes/ References**
	Long term (Beyond 5 years up to 100 years)				
Fossil Fuel, Plastics	Impacts from enhanced global warming leading to drastic climate change	Likely	catastrophic	Moderate -High Treat risk	Refer to Table 26
	Scarcity due to intense global demand/ decreasing supply	Likely	Moderate	Moderate -High Treat risk	
	High impact health effects from combustion (chronic: cancer)	Likely	Moderate - catastrophic	Moderate -High Treat risk	Wilkinson et al., 2007; Dockery et al., 1993; Craig et al., 2008
	High impact health effects from exposure to plastic manufacturing (chronic: cancer)	Likely	Moderate - catastrophic	Moderate -High Treat risk	
	Decreased availability of fossil fuels for purposes other than energy/transport	Very likely	Moderate - catastrophic	Moderate -High Treat risk	
	Increased dependency on coal exacerbating global warming and health effects	Likely	catastrophic	Moderate -High Treat risk	

The results of the risk assessment are given in two tables in Chapter 6 (Table 26 and Table 27). The first table (Table 26) is the generic risk table showing some of the risks from the impacts to the Earth system with respect to how those impacts would affect the human socioeconomic systems, the wider environment, etc. These risks are as a result of the impacts caused by the product system and can be classified in a number of ways such as according to where the risk event occurs as well as when it occurs with a time frame from 0 to a 100 years. The second table (Table 27) consists of risk to the product system and these are from various impact causing substances within the product system. The impacts are mainly from the resource that is used in abundance. These two risk tables can be thought of as components of panarchy as shown in Figure 49.

The arrows from the K phase to the α phase represent events that are to be remembered and passed down from the larger and slower higher level systems to those that may be affected by changes related to the knowledge or events. Thus arrow A and C passes down knowledge to be remembered. The arrows from the Ω phase to K phase represents revolt, where the smaller and faster cycles can affect the larger and slower ones above them. Arrows B and D thus contain events that may influence the larger systems.

Arrow A represents events to be remembered, the knowledge that can affect the product system are passed from the Earth CAS to the product CAS. This knowledge can in the form of external risk as well as risk reflected from arrow B, which represent events that can influence the Earth system from the lower level product system. For example, the product system results in greenhouse gases that lead to global warming affecting the Earth system (Arrow B). Global warming results in sea level rise, extreme weather events, etc. that affect the product system (Arrow A). The risks pertaining to these (A and B) can be found in the first matrix (Table 26).

Arrow C represents events from the product system that can affect the supplier systems below. Examples of these include requirements placed on the supplier by the product system such as a predefined recycled content in material for the components, the availability of environmental management systems to reflect the supplier’s dedication to environmental performance, policy for social responsibility, etc. Arrow D represents events from supplier systems that can have an effect on the product system. These can include events such as resource scarcity causing a shortage in components into the product system, or social unrest causing component scarcity where lack of labour makes it impossible to supply the product system with the required components. The events can range from risks to the system from critical needs either stemming from issues with suppliers, regulations affecting suppliers, etc. Note that there are many other CAS between the supplier systems, the product system and the Earth system, each connected and feeding into the cycles of others.

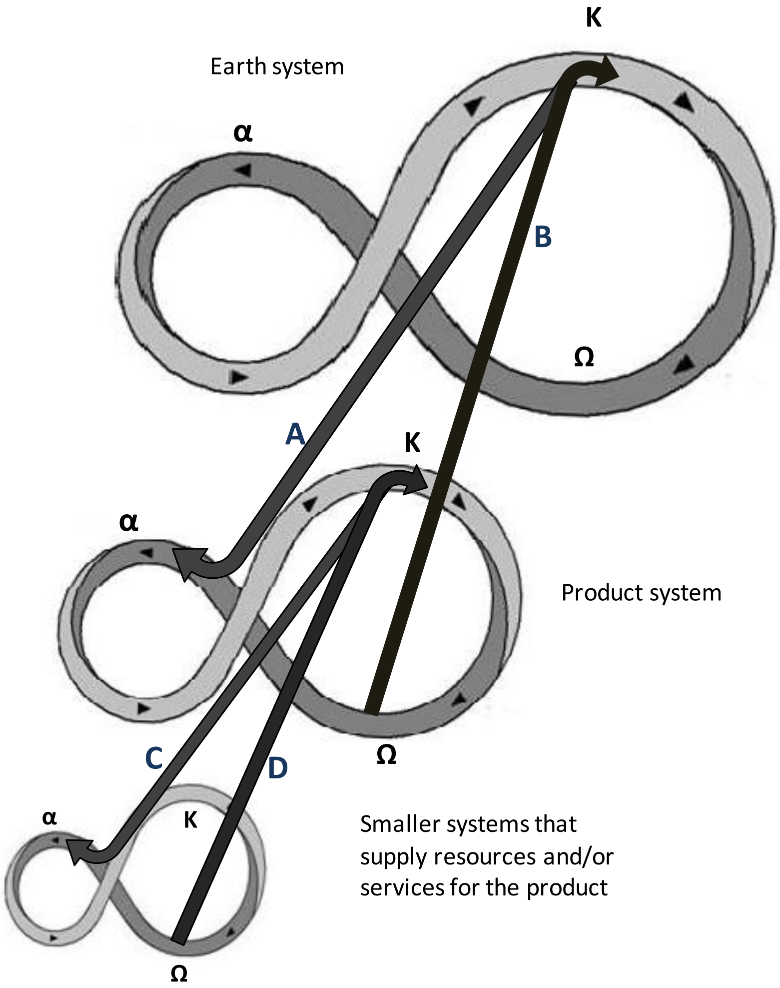

Figure 49: Nested hierarchy of CAS associated with the product system showing "remember" and "revolt" arrows which are synonymous to risk knowledge or risk events (modified from Holling (2004))

Risk to the Earth system

The LCA is instrumental in identifying the impacts from the product system. As seen from Figure 43, there are impacts for each impact category thus reflecting the possible risks. The LCA results cannot help identify the most significant impact category as that depends on the current state of the Earth system. If the Earth system is stressed due to ozone layer depletion, the respective category can be focused on to determine where the impact are coming from within the product system. The LCA inventory then allows the impacts to be traced to the root causes within supplier systems or within the product system itself. Note that risk to the Earth system is invariably a risk to all other systems though some of the risks would be absorbed by the higher level systems.

The global risks from impacts such as ozone layer depletion, resource depletion and global warming can affect all socioeconomic activities while impact such as acidification and eutrophication are significant on a regional or local level where the impacts are aggravated and the risks become greater if the regions or locales are already suffering impacts for extended periods of time. While the matrix (Table 26) attempts to include potential risks across the social and economic systems, the ones given are primarily environmental since these correlate directly to risks to the Earth system. Further risk to the Earth system, for example from social needs (Peet and Boseel, 1999) can be investigated by including impact categories relating to social systems.

Risk to the Product system – Resources

Fossil fuels are fundamental to all industry and this is also true for the product system considered for the research. Considering that increased world demand is likely to drive prices higher, NZ might find overseas resource procurement somewhat difficult in the long-term, especially in the event of fossil fuel scarcity. Geopolitical risk can also affect the supply and price of resources in general, and again, this is specifically true for fossil fuels.

From a NZ-based production system perspective, the proximity of resources is of major concern. For example, all plastic resins, approximately 260 million kg in 2005, are imported (Plastics New Zealand, 2006); this means NZ is highly dependent on global supply and prices. Any shortages in resin, brought on by potential scarcity of fossil fuel would have adverse impacts on NZ plastic-based production systems, unless drastic changes to design can be quickly implemented. Hence, the proximity issue could potentially exacerbate the economic impacts created by resource scarcity. The export of goods (as opposed to intellectual property and services) is a significant source of revenue for NZ and the proximity issues that apply for exports are unavoidable. However, the costs involved in imports may be greatly reduced via locally sourced resources.

When considering the temporal scales with respect to resource scarcity, the issues are fairly minor in the short-term. The significant risks in the short-term are of economic nature where resource pricing result from global market conditions. These conditions have little to do with the actual amount of resource available. However, when the long-term is considered, especially for fossil fuels, the availability or lack thereof, is likely to have greater impacts on resource pricing as competition for remaining resources escalate. In terms of spatial risks, the short-term and long-term risks are locally concentrated. For example, fluctuation in price, a short-term risk, affects the production system directly while scarcity, a long-term risk while having global implications, would still affect the production system, although with potentially higher impacts.

<u>Risk to the Product system - Health and environmental degradation</u>

Risks contributed from the spatial scale highlight waste, emissions, health of workers and general public, and environmental degradation, as potential risk factors to the production system. The risks involved are aligned with the procurement of minerals such as aluminium and bauxite, where resources are mined and processed locally. Hence most of the local risks also carry economic risks in terms of regulatory compliance and in the event of failure, legal and risks to reputation are also of concern. With respect to electrical energy, NZ's use of renewable energy sources is favourable, where approximately 71% of electricity generated in 2005 was from renewable sources (hydro, geothermal and wind) (MED, 2006) Hence the risks from electrical energy related issues are less significant for the short to medium term, but increasing consumption beyond renewable capacity is increasing reliance on fossil fuels for electricity production. Additionally the advantage from renewable electrical energy can be affected by climate change in the long-term.

From a temporal perspective, there is significant risk to health and environment when considering all temporal scales. The health risks from short to long term scales range from acute to chronic effects respectively, while more serious conditions such as cancer are potential risks in the long-term. Likewise, environmental risk increases with time, where accumulation of impacts may seriously undermine the ability of the environment to regenerate itself. On a spatial scale, health risks are of significance both locally and globally, regardless of the temporal scale. However, the higher impact risks for the environment are likely to have global significance.

It should also be noted that other aspects such as quality, market requirements, etc. are also important for the sustainability of the production system. In fact, they are more significant for the day-to-day continuation of the system. The concentration of resources for planning for these risks may be the reason that businesses only consider planning only up to five years. Additionally, while examining the generic risks to the selected resources, the potential opportunities must also be taken into account. More efficient sources of energy and transport, emergence of new high performance materials that are not fossil fuel based, etc. may result from the need to sustain the production system. Thus attempts at ensuring sustainability of the production system should also go hand in hand with evolution within the system.

6.2.5 RISK TREATMENT

After the risks have been evaluated, action according to the level of risk needs, in this case resulting in either accepting, controlling or treating of the risk, needs to be taken. Each risk event needs to be analysed with possible future scenarios in order to determine feasible actions. Each risk would have different treatment options and methods that need to be analysed prior to implementation. It is imperative that risk assessment of the treatment be undertaken in order to determine possible consequences such that treatment of one area of unsustainability does not lead to unsustainability in another. The treatments would depend on who controls the risk, the available resources, urgency of risk event, etc. Some of the treatments for the risks above would include:

- Substitution of materials and processes which would result in less risk;
- Control the risk by changing parameters of a process;
- End of pipe technology to minimise risk from emissions;
- Mining of wastes to remove hazardous substances;
- Use of green chemistry or green design principles for designing product or process;
- In the case of high energy intense materials, use less of the material and if possible the material should have a high recycled content rather than it being virgin;
- Conservation of resources;
- Support conservation efforts by other organisations;
- Eutrophication – filtration of nutrients and algae, radiation; and
- Reduced exposure to chemicals during manufacture of components; etc.

Chapter 7 will discuss more treatment options together with how complexity of systems needs to be taken into account for success.

6.3 CHAPTER CONCLUSIONS

This chapter was aimed at presenting the use of the model within the context of a design and manufacturing organisation. The results for implementing the model are given for a case study within the office furniture industry in New Zealand. The case study consists of carrying out life cycle impact assessment to determine risk to and from the product systems. The risks were analysed and evaluated using simple risk matrices in this case. There are two risk matrices for a case study, the risks to the overall system from the impacts and risks to the product system from the hotspots. Together they can give ample indication of the risks facing the complex system in which the product system functions. Discussion of results for the case studies and the application of the model are given in Chapter 7 together with a critique of the model and ways to improve it. Furthermore, the use of risk for assessing sustainability is discussed with respect to whether the results from such a model may lead to sustainability.

CHAPTER 7: DISCUSSION

Chapter 6 illustrated how the model can be implemented via the use of a case study. The results show the flexibility of the model with respect to the choice of impact assessment methods and risk assessment methods. This means that the assessment may be streamlined or carried out in full depending on the resources at the practitioner's command. The case studies were at best streamlined versions of the proposed model as data would need to be gathered for more complete versions to truly capture the complexities within the system. The results obtained as well as findings during implementation of the model are discussed in this chapter. Further discussion of how complexity needs to be taken into account, possible improvements to the model as well as the role of risk assessment and management in sustainability is given together with what a sustainable office furniture product and company might entail for the future. The discussion section is thus divided into two parts as follows:

1. Critique of the model components including the shortcoming and areas for improvement; and
2. Discussion of risk with respect to sustainability.

7.1 THE MODEL: CRITIQUE AND POTENTIAL IMPROVEMENTS

One of the main objectives of this research was to develop a new model to assess sustainability by integrating existing methods and models. The existing methods chosen for integration, LCA and RA, are tools that have longstanding use in the scientific community. The concept of risk, a very simplified version, was used as far back as 300B.C. where the analyses were conducted by the Asipu in the Tigris-Euphrates valley (Grier, 1980, as cited by Covello and Mumpower, 1985) whose methodology was remarkably similar to current analysis, albeit devoid of probability theory, which was first introduced in 1657 by Pascal (Covello and Mumpower, 1985). The concept of environmental risk, as we now know it, was developed in the 1960s as a response to environmental concerns such as environmental contamination and high impact events (Burton and Pushchak, 1984). LCA too began its existence around this time, in 1969, although, more specifically called a Resource and Environmental Profile Analysis (REPA) when (Coca Cola) beverage containers were compared to determine the type of container that led to the least impact on resources and environment (Hunt et al., 1992).

The two methods have already been integrated for various purposes, specifically in improving upon their own methodologies as discussed in Chapter 5. The model contained in this thesis was to be simple, and designed to be implemented by non-experts with elements of existing standardized frameworks available through standards organisations (ISO 14040:2006, ISO 14044:2006, ISO 31000:2009, AS-NZS 4360-2004, ISO/IEC 31010:2009) thus capitalising on the existing body of literature and existing support institutions that may be helpful in overcoming practical limitations of each method. The model is designed to investigate a system with respect to risks that may prevent the continued existence of the system. It does this by analysing the possible events, both internally and externally, that may threaten the system. While it does not explicitly inform the practitioner regarding whether or not the system itself should continue to exist, it indicates the potential risks to other systems on which humanity relies upon. The choice to take action to minimise the risks to other systems remains to be a value judgement based on the beliefs of society as well as the critical nature of the risk.

7.1.1 COMPLEXITY IN THE MODEL

In order to determine whether the model is able to assess for sustainability of complex systems, the criteria used to identify the components of the model are revisited from Chapter 3. The criteria and how they are included or recognised by the model are discussed to show that while some criteria are indeed recognised directly, some are only indirectly recognised. Additional components and means to improve the model to fully include and recognise all the criteria are described in the following sections.

Criterion: Recognising the existence of multiple agents and system levels

The scoping stage of the model defines the systems that will be included in the assessment. The model allows different types of assessments ranging from streamlined versions with select systems, to full versions with the three relevant systems (social, environmental and economic). Multiple agents are recognised via the use of the inventory step. At this step, multiple agents that play a part in the product system are identified with respect to the locations at which they influence the product system. For example, aluminium components and processes for producing those components may be defined as separate agents of the system. Likewise, other resources and processes are individual agents either within the same system or in different system levels depending on allocation of the agents and systems. Thus LCA and the RA components of the model both recognise the existence of multiple agents. The LCA does this by analysing different processes within the product system; and the RA recognises multiple agents by analysing risks from multiple sources within and across systems.

Furthermore the choice of impact categories at the impact assessment step also introduces different elements of systems within which multiple agents exist. For example, an impact category such as global warming is associated with not only the temperature regulation of the Earth system, but also hydrological cycles, carbon cycle, etc. which are both different levels of the Earth system and complex systems themselves. While LCA mainly utilises environmental impact categories, social and economic categories used in LCC and SLCA can expand the number of agents and systems analysed by the model. The inclusion of different systems including their interconnections is a requirement for holism as will be explained later.

<u>Criterion: Recognising interconnections and interdependencies</u>

When the model investigates the life cycle of the product, it reveals most of the interconnections with respect to material resources within the product system. An example of the interconnections has already been given in Chapter 5 (also shown below as Figure 50) where each component is connected to other subcomponents.

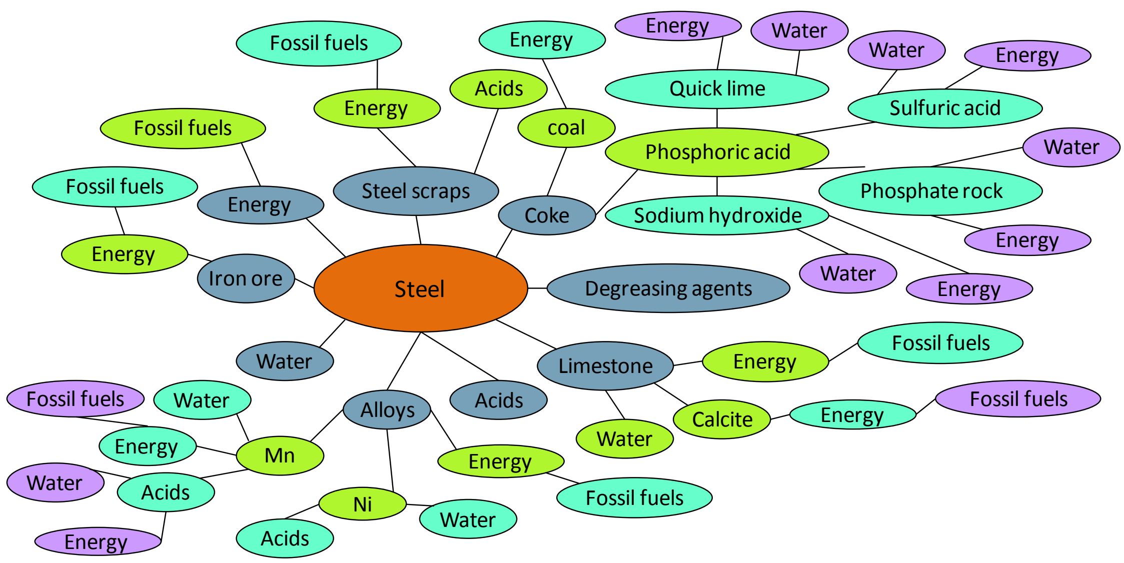

Figure 50: Interconnections associated with components

The RA component of the model analyses how a risk event can have impacts across different systems and thus taking interconnections and interdependencies into account. Much like the multiple agents and system levels, one risk in a specific level can become another risk at another level. For example, ozone layer depletion can be a threat to the Earth system where harmful rays can cause health effects for fauna and destroy flora. Considering that human beings depend on the ozone layer to filter out harmful rays from the sun, depletion would result in health impacts, which in turn would affect the social and the economic subsystems via the health subsystem. Interdependencies are also implicitly recognised throughout the lifecycle where the product system depends upon the smaller systems that provide components of services to manufacture the product. For example, the company depends on its suppliers for the components, the employees for services, the infrastructure and even the climatic conditions for utilities such as electricity in the case of hydroelectricity, etc. The suppliers and employees depend on the company for their business and work respectively. The connections to these dependencies are made when analysing the product system at both the LCA and the RA stages.

Criterion: Taking system dynamics into account (time and space)

System dynamics are taken into account mainly at the RA stage where the risks are classified according to whether they occur locally, regionally or globally, together with what to expect at different time scales (short, medium and long term). The dynamics of the systems may lead to changes in the agents and behaviour of the system. Keeping track of changes within the system together with how risk events will influence and change the system are crucial for sustainability. With an in-depth assessment with more data, dynamic modelling of the system's risk events could be carried out. Figure 51 shows how a system may change with time and space. The risks at each point in time and space would be different with respect to the different ecosystems at the space and how sensitive they are to the actions of the system. As the system changes, so too would the risks associated with the system. This is one area of the model that could be improved with the use of more vigorous modelling tools to simulate and map out how different risks change over time together with how the systems themselves change over time and space.

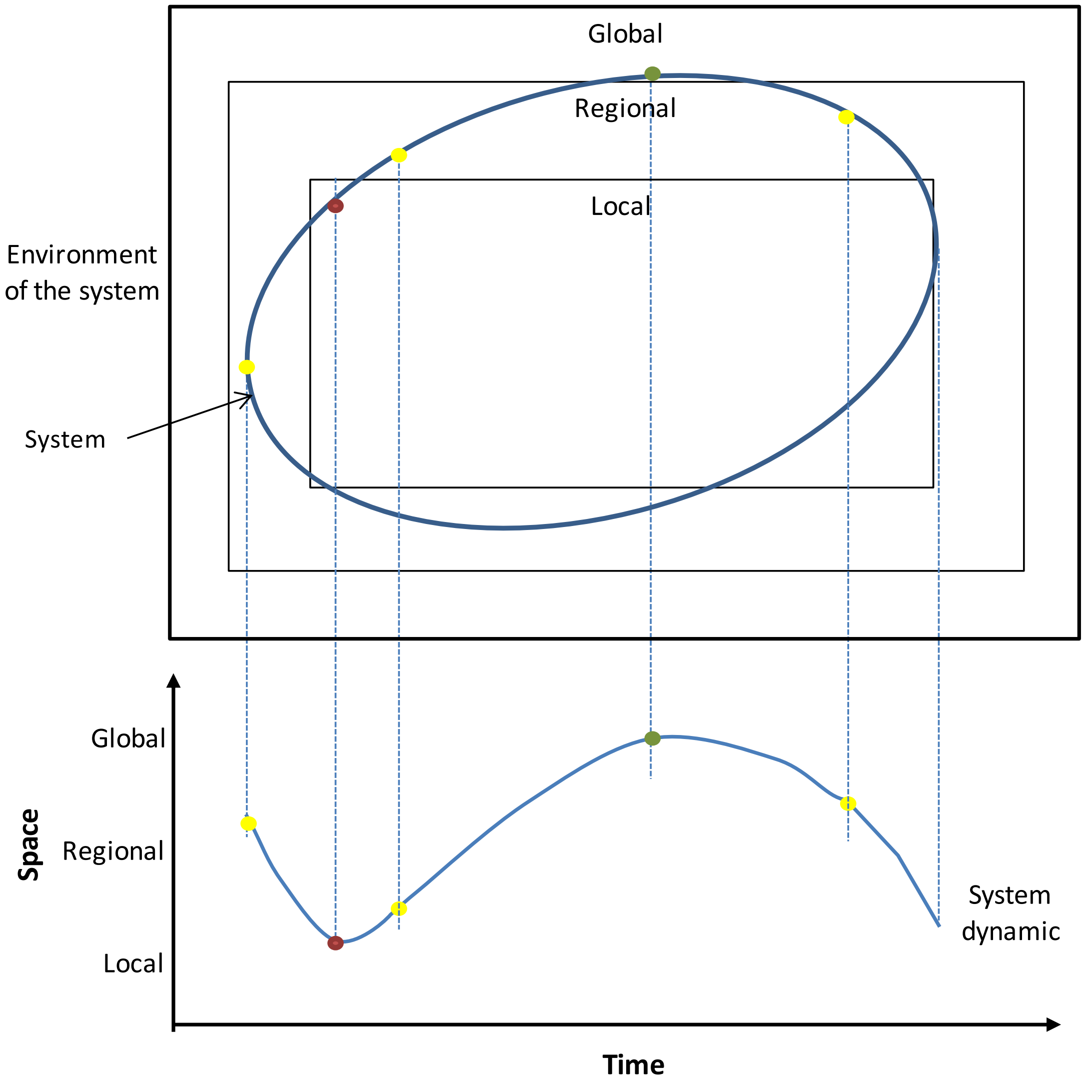

Figure 51: Tracking system dynamics through time and space

Criterion: Recognising system limits or thresholds

The model recognises system limits when evaluating risks and determining how to respond to the risks. The level of risk as well as the corresponding actions to take depends on the proximity to limits or thresholds as shown in Figure 52 and Figure 53. Figure 52 illustrates how the system behaves within the upper system limit, which is equivalent to the system boundary in this case. The level of risk indicated by “low”, “moderate”, “high” and “extreme” is used to map the changing level of risk faced by the system as it moves closer and further from limits respectively. The level of risk also dictates the actions to be taken where the actions can range from accepting the risk, controlling the risk or mitigating the risk. While the upper limit for the system is placed at the boundary of the system, the lower limit may be located anywhere within the boundary.

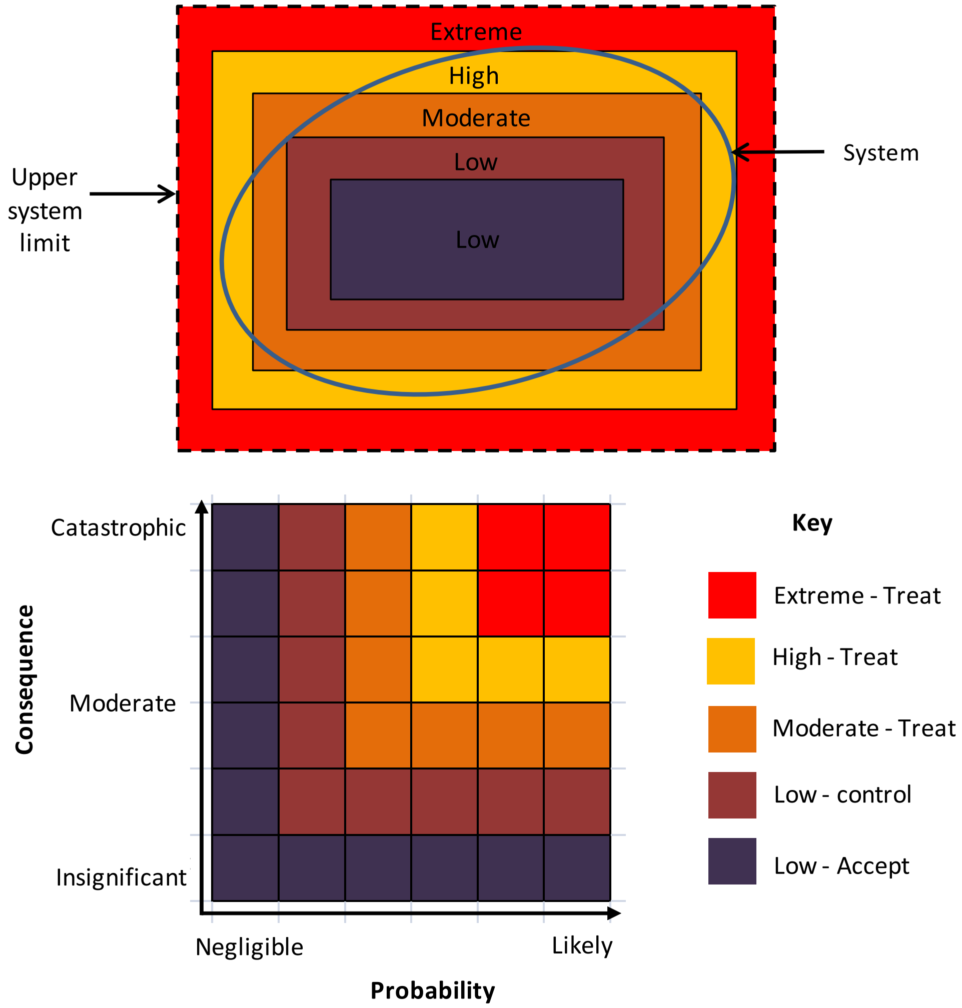

Figure 52: Path of the system with respect to level of risk

As shown by Figure 52 and Figure 53, the system may function closer to the limits or further from them at any given time or space. Thus if a risk event is likely to drive the system closer to a limit, the risk would be classified as extreme and assigned some means of mitigation. The risk level becomes extreme when the system is near its limits (both upper and lower limits). While recognising limits or thresholds can determine the level of risk, the model could benefit from a component that is able to track limits with respect to the dynamic nature of each system. As mentioned earlier, due to the dynamic nature of systems, the limits or thresholds can also change dynamically.

Figure 53 shows the lower and upper limits of the system by the broken red line and the solid red line respectively. The solid red line represents the absolute limit beyond which the system would shift regimes and change drastically where function of the system could be lost. Furthermore, within a dynamic system, the risks may have different effects corresponding to changing limits or thresholds as well as sensitivity and health of the system. Additionally, the system limits and the system dynamics is likely to change if and when upper and lower level systems change. Thus the model could benefit from a method to visually keep track of how limits change within all relevant systems and how the changes would impact upon the level of risk at any given time or space. Dynamic modelling and tracking of limits via simulations with varying parameters are recommended as a means to improve the model.

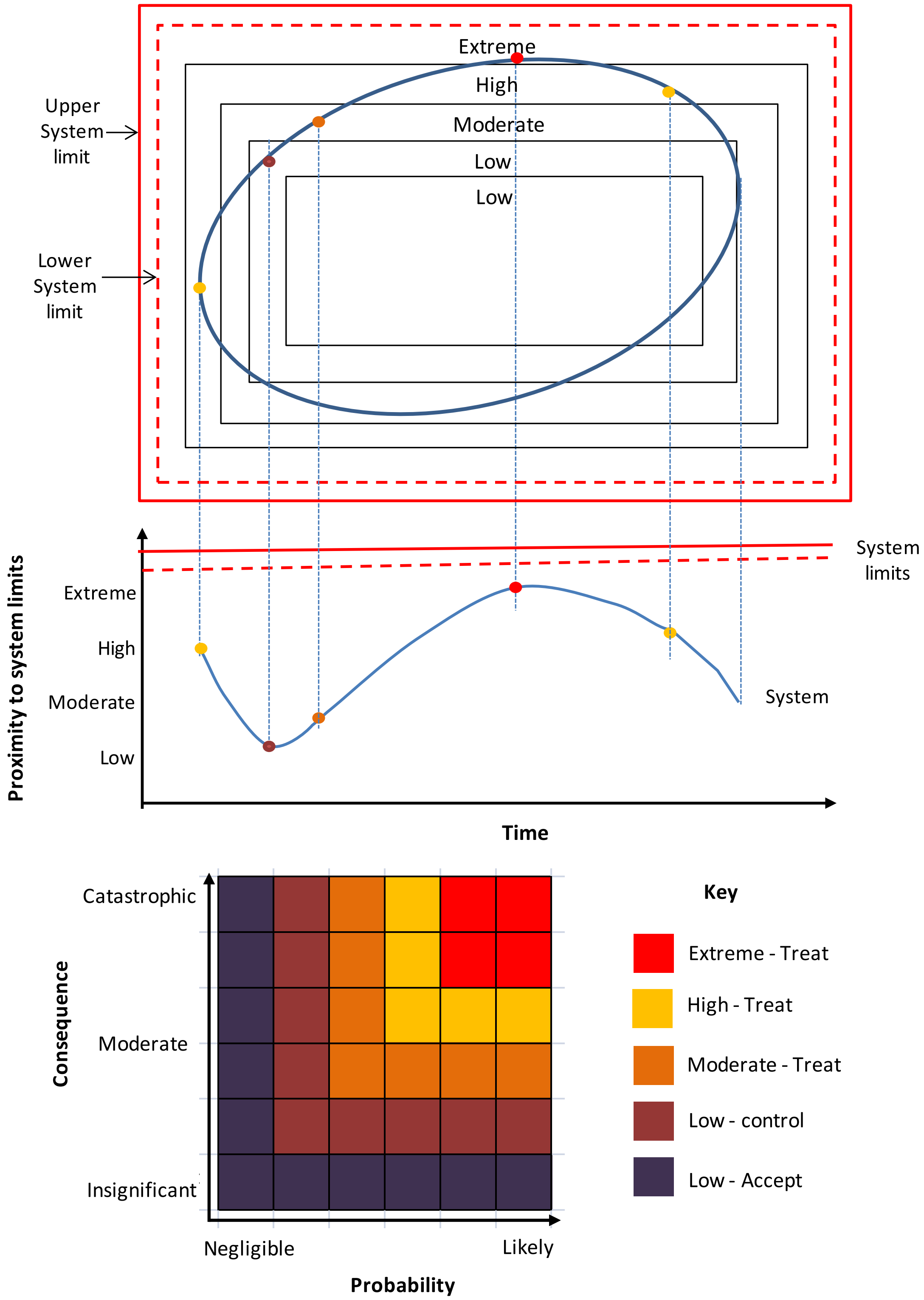

Figure 53: Risk evaluation matrix according to proximity to system limits/thresholds

Criterion: Recognising resilience and adaptive capacity

Resilience and adaptive capacity are central to sustainability and are considered at the evaluation stage of the model with respect to how the system may respond to the measures taken to mitigate risks as well as how it changes due to internal and external risks and events. Resilience, or how the system is able to cope with changes, is not only about the proximity to system limits, but also how the system manages to retain its properties and functions despite changes influenced by internal and external sources. The ability of the system to function within the changing limits and environment is a good indication of its resilience. Mitigating risks could help build resilience of the system as actions taken to mitigate could help preserve elements that are critical for its function. For example, if the company is aware of aluminium scarcity, it could contract extra suppliers to keep supplying the product system. The increase in the number of potential sources of aluminium, or increased diversity of supply, would mean that the failure of one source would not cripple the product system.

With respect to actions that mitigate risk, the possible mitigation procedures per risk need to be analysed with respect to how they could change the system parameters and behaviour. Mitigation could affect different systems across levels. For example, the additional supply of aluminium sources would impact the economic system with increasing cost to the company. It should also be noted that mitigation of some risks may create risks either within other stages of the lifecycle (shifting of risk), or within a subsystem that is connected to the action. One example of this is end-of-pipe technology to mitigate impacts from pollution. While the pollution may be prevented, the technology needed to capture the pollution requires its own product system with its own impacts.

A complete analysis of all system levels would help reveal a wider range of risk events while streamlined versions of the assessment would fail to do so. The main issue with this is that huge amounts of data from within the system and across system levels need to be compiled in a centralised manner. This information needs to span over different types of risks including their dynamics with respect to time and how they influence different systems. The ability to use such data would mean the practitioner is able to consider more possibilities within the complex systems and hence be better prepared to initiate mitigation and adaptation procedures for the continuation of the system function.

Criterion: Being holistic

As mentioned previously, the model can be implemented as a streamlined assessment or a full assessment. In order for the model to be complete and holistic, it needs to investigate all systems and subsystems that are connected with the product system. While this may be impractical considering the data requirement and time availability, holism requires at least the environmental, social and economic systems to be included because without all three systems and their interconnections, the model ceases to be a sustainability assessment model. As mentioned in Chapter 3, it would also be ideal to include components such as community and business as they are significant subsystems of society. However, it is envisioned that addressing the most critical elements of the environmental, social and economic systems, i.e. treating the most critical risks from each system, would be beneficial and perhaps even sufficient for sustainability. If a practitioner is to be successful, they need to have information on all potential risks, those that are incoming as well as outgoing from the product system (Figure 54).

While there is certainly potential for complete assessments of sustainability using this model, readily available data are crucial for good timely results. A centralised database would be beneficial for managing a system for sustainability. This database could contain information on different systems, ecosystem behaviours, weather patterns, social patterns and scientific data ranging from the life cycle of diseases to the solar cycle, all of which could affect a product system.

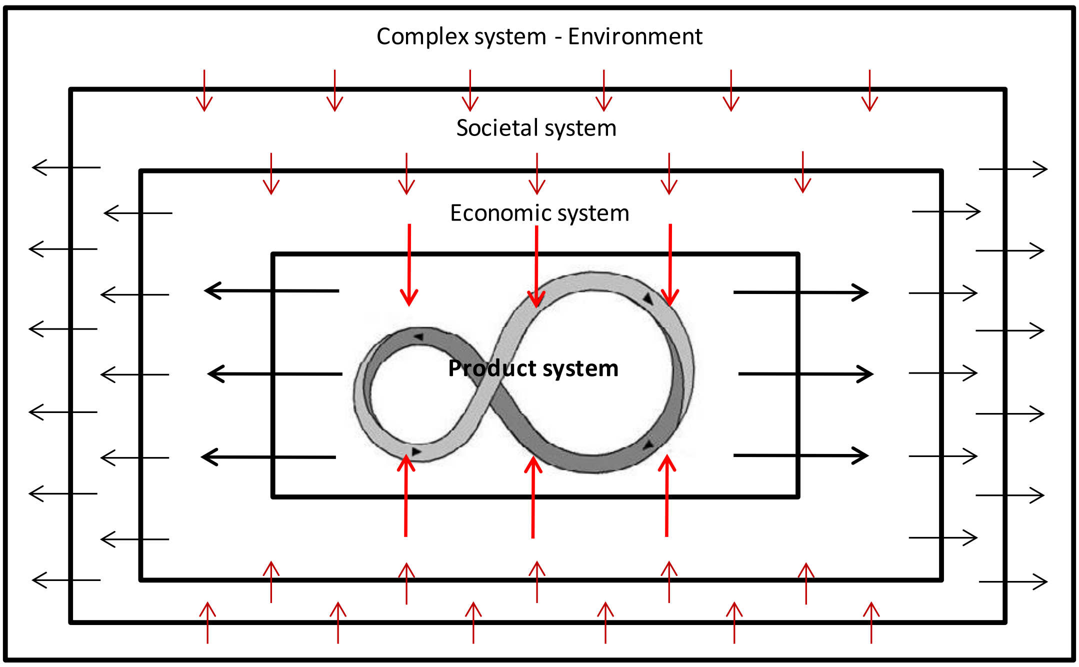

Figure 54: Risk to and from the product system propagating through systems

Science in the model

The last criterion when developing the model was the scientific validity and use of science within the model. Indeed there are numerous ways in which this model utilises scientific knowledge, integrating science of LCA and RA for calculation and analysis, to iteratively generate new knowledge about the systems. The model makes use of hard science in calculating impacts associated with the product cycle using various accepted methodologies in the scientific community. The risk matrix method which was used to illustrate the application of the model has various advantages and disadvantages that will be discussed in further detail. While it is one of the simplest forms of RA, it allows for risks to be identified and analysed in a qualitative manner. The analysis methodology can be improved by using quantitative or quasi-quantitative methods as given in Chapter 5. Furthermore, the model itself is a scientific instrument for furthering knowledge about systems and sustainability via identification and mitigation of risk as is discussed in the final section of this chapter.

7.2 CRITIQUE OF THE MODEL

Given that the model utilises existing methods, disadvantages and advantages common to each method are expected to appear in the new model. There are some exceptions to this where the use of RA improves LCA's shortfalls and vice-versa. LCA's lack of spatial resolution was resolved in two ways: 1. Identification of the locations and movement of resources from one life cycle stage to the next meaning that the data record would contain where the resources are coming from and where the emissions and wastes are going to; and 2. Differentiating the impact categories according to whether they occur locally, regionally or globally. Likewise, LCA's lack of temporal resolution is solved by: 1. Differentiating impact categories according to when the impacts are likely to occur; and 2. Identifying risks according to expected impacts per chosen time frames corresponding to the type of system that is assessed.

In the case study used to illustrate the application of the model, three timeframes were used: 1 year period; 5 year period; and up to 100 years. While sustainability of Earth systems need to be beyond a mere 100 years, it is unlikely that a product system such as that analysed for this study would last for 100 years, at least without changes to the various subsystems and practices involved. The time scales are to be adjusted according to the life time of the object assessed. This means that the model is transferable across industry and potentially be used to assess services as well as products.

The use of the functional unit was preserved and serves as a starting point to initiate the gathering of data to understand the system that is to be assessed. This leads the way for the scope of the assessment to be defined. While the integration consists of marrying the impact category risks with the risk from within the product system, the model remains to be somewhere between an LCA-RA hybrid and a toolbox utilising the two methods in series. While Udo de Haes et al. (2006) may not consider this as a full integration of the two methods, the model seems to be capable of assessing sustainability with the focus on revealing critical events that may lead to unsustainability of the system. The system is only as strong as its weakest link and strengthening the system by mitigating risks and building resilience and adaptive capacity through planning for risks may lead to sustainability.

Figure 55 is a flowchart of the expected events when implementing the model developed in this thesis. Once the risks are identified and analysed, they need to be ranked in order of priority such that mitigation can be prioritised. For the case study presented, the highest level of risk is designated as “extreme” with the next level below being “high” and so on. The three risk levels, extreme, high and moderate were chosen to require mitigation because the risks could eventually cause the demise of the product system itself or cause irrecoverable harm to higher level systems. The risk from the remaining levels is to be controlled or accepted. After determining whether the risk needs to be mitigated, means to mitigate them should be identified. Once the means for mitigation has been found and implemented, the risk event is expected to be resolved and thus the risk ceases to exist and a means of unsustainability eliminated. However, it isn’t always the case since actions in one area may trigger other risk events in neighbouring systems and hence the model is to be reiterated for continuous assessment.

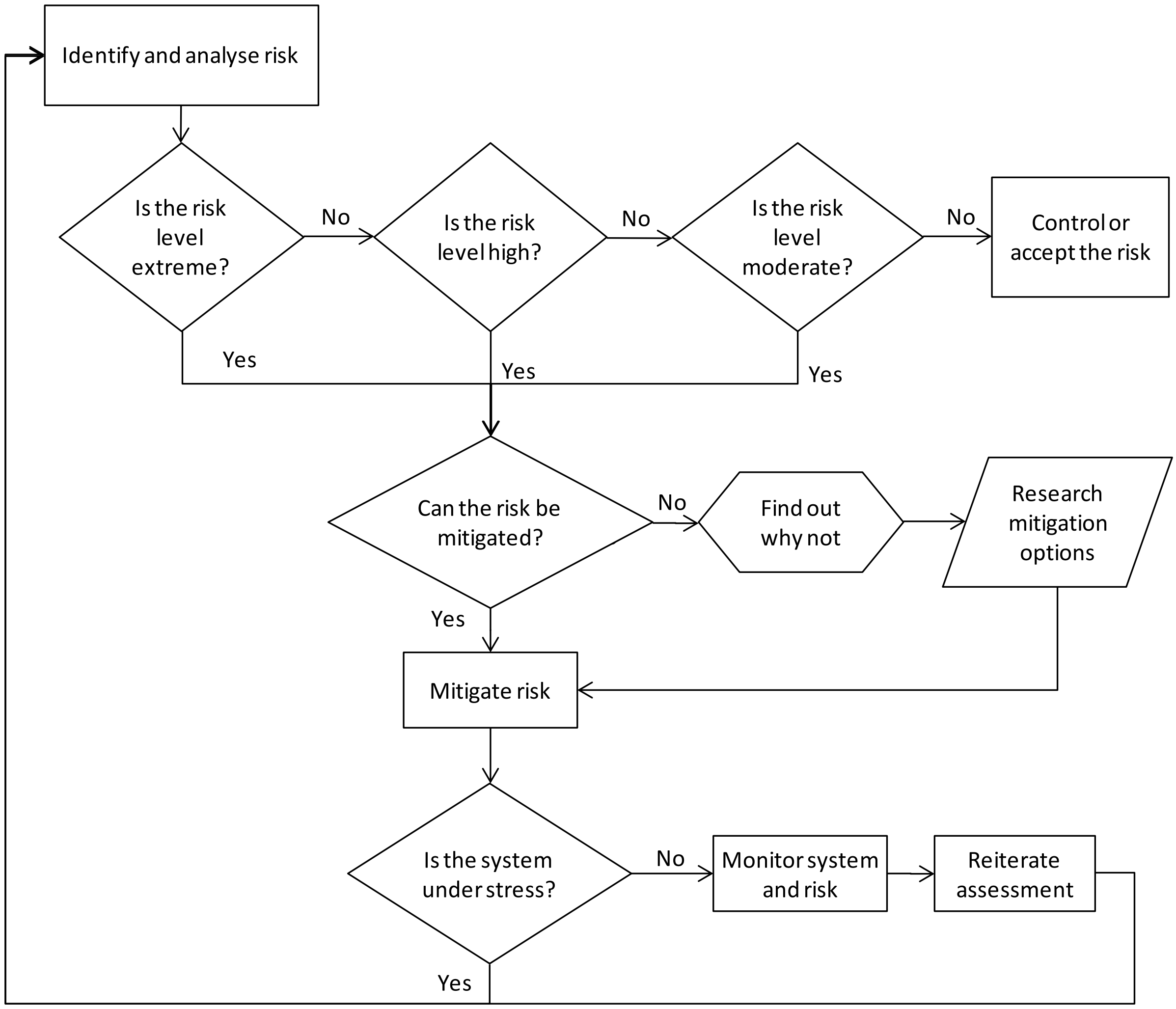

Figure 55: Sustainability of system via risk assessment

Other potential deficiencies of the model are common for many assessment methods and models in existence. These deficiencies include issues with data availability, need for expert knowledge, uncertainty, transparency, communication, etc. Since the two main methods integrated have been used extensively in the scientific community, transparency and communication of results would follow similar procedure as that of the individual counterparts of the model. I.e. the LCA stage of the model would produce graphical or tabular results of the impacts per impact category highlighting the life cycle stages that are significant; the materials or processes that are significant; etc. while the RA is capable of presenting matrices ranking the identified risks according to order of priority.

There are numerous sources of uncertainty within the model, mainly associated with unknowns such as how systems may react to certain events, how limits may change, unknown future events, human error, uncertainty from the use of certain methodologies for LCA and RA, etc.

Methodology for risk assessment can vary according to the goal of the assessment and choice of method to use is up to the practitioner. According to Skelton (1996), while methods are available to quantify the probabilities of human error, their validation is problematic with different methodologies producing different results. This is due to the uncertain nature of risks. Excessive reliance on numerical risk assessments can be a significant limitation and according to some researchers, rigorous risk quantification is seen to be unnecessary for management purposes. However, while it is said that qualitative RA is more effective (McClellan, 2003), the approach suffers from the need for extensive data and can also be difficult to communicate.

Another potential issue with the model concerns unknowns. While the model is able to identify risks, there are bound to be limitless unknown risks with unknown consequences, any of which could cause unsustainability. This must be accepted, and to counter this to some extent, there should be a pattern of constant monitoring and data gathering. Reiteration of the model should increase the body of knowledge available to make effective connections between potential causes and effects, potential mitigation measures and how the system would respond to mitigation at any given time.

One thing that seems to be lacking in the model is the opportunity side of risk as risk events can both lead to advantages and disadvantages according to the final consequence. For example, depopulation of the planet can be an advantage as it relieves the anthropocentric pressures on the planet (more resources for few beneficiaries). However if depopulation occurs by premature death, components (agents) of the social system are destroyed, diversity is lost and hence the final result could be unsustainable. Additionally, there are ethical issues involved in what might be considered as opportunities and acceptable risks. Further issues include possible overconfidence that may result in false sense of security once analysis and mitigation has been carried out. One significant thing to remember about the model, as with the use of any other model, is that decisions can only be made with the information available at a given time and the assessment cannot replace sound decision making. The model is an aid to decision makers where identification of potential causes of unsustainability may give them a chance to tweak the system so it behaves sustainably. In order to do that, a good definition for sustainability and an idea of the ultimate goal for sustainability should pre-exist. Discussion of whether the model is expected to be successful at decision making level is discussed in the final section of this chapter.

7.3 PROPOSED IMPROVEMENTS TO THE MODEL

Carrying out RA should help answer some of the following questions:

1. What are the risks associated with the impact categories and resulting hotspot or from LCA?
2. How would the risks change with time?
3. Which risks are priorities within the context of sustainability? and
4. What are the likely outcomes if changes are made to mitigate the identified risks?

The first, third and fourth questions can be answered via existing literature, expert knowledge, workshops, etc. The second question is subject to events in the future which may be estimated with increasing uncertainty. Uncertainty with respect to future events cannot be overcome simply because they remain in the realm of the unknown. However, as mentioned in Chapter 2, different potential scenarios can be generated via simulation and extrapolation, etc. to indicate possible futures. Examples of cases where potential scenarios are generated include climate change and human development (population, fertility, etc.) related reports. These may help identify a range of possible future scenarios to help understand what could happen in the future. While it is not a necessary part of the model, more information on the outlook of the environmental and socio-economic state during the assessment could help generate possibilities and risks for different futures according to some of the external events taking place in the world. With different futures, probabilities and consequences pertaining to risk are subject to different changes. Since the aim of sustainability assessment is to obtain information on the direction of a venture, information on the potential risks with respect to different future scenarios could come in use.

Possible futures

In order to take into account the possible futures, the risk assessment can be embedded within selected possible futures. For the purpose of this research, scenes from a study by New Zealand's Landcare described in "Future Scenarios for New Zealand" (Taylor et al., 2007) were used (Figure 56). The work was chosen for the generic nature of the four main scenarios.

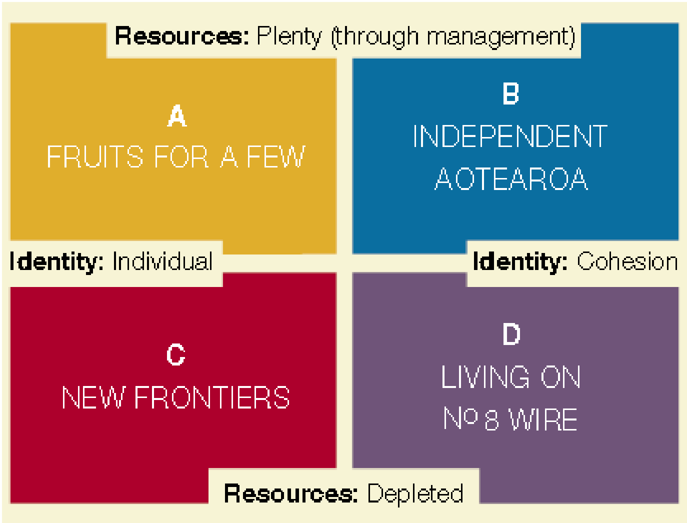

Figure 56: "The logical grid used to locate and distinguish scenarios (Reproduced from Taylor et al., 2007)

These are four hypothetical futures based on trends and creative thinking. The authors describe each scenario as follows (Taylor et al., 2007, pp11):

A. "An economy with unevenly distributed benefits (80% to minority elite: 20% to the rest);
B. An economy with equity and very different 'genuine progress' indicators taking the place of GDP growth targets;
C. We might stay globalised and 'hit the wall' of resource and ecosystem limitations (after several decades), resulting in economic crash and social conflict; or
D. Avoid the social conflict 'at the last minute' by creating a localized, inward-looking lifestyle on a depleted resource base".

More explanation of the scenarios with respect to driver differences, environmental related trends and technology in each scenario are found in Taylor et al. (2007). This research uses a similar grid to base the risk assessment. In this case the assessment is conducted using a scenario E which is in the middle and not yet in any of the extreme regions that are A, B, C and D (Figure 57) thus indicating the potential for the future to change for the better (B), for worse (C) or a mix of the two (A and D). Different scenarios for different regions may also be developed however; this research retains the generic possibilities.

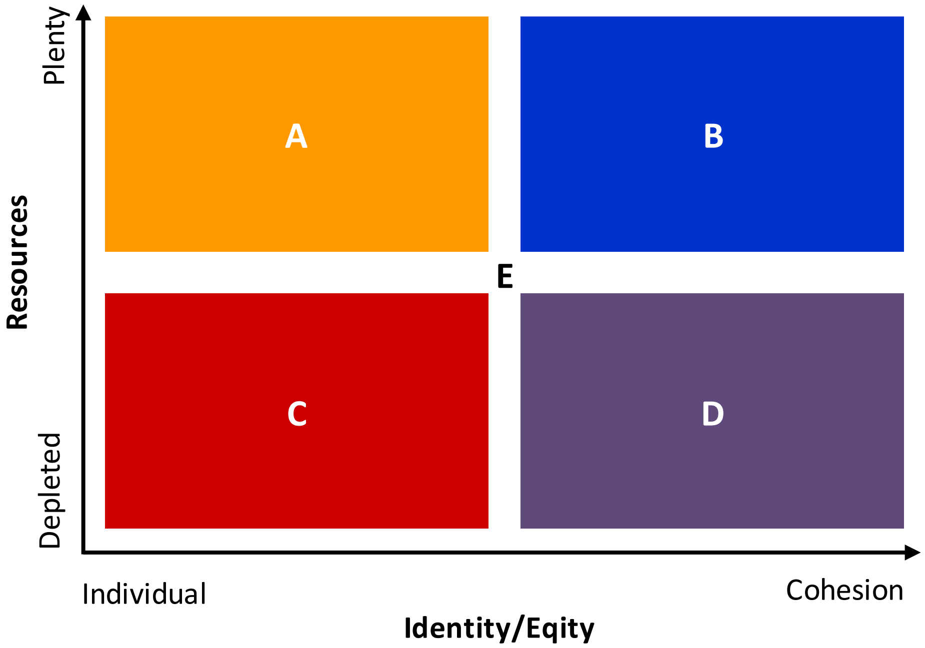

Figure 57: Four scenes used to embed the risk assessment (modified from Taylor et al., 2007)

One of the recommendations of this study is to acquire different sets of future scenarios and implement the methodology within those futures. One of the advantages of having multiple futures is that when more futures are available, more information can be gained on how the system may interact with other variables. One of the disadvantages is that the sheer number of possibilities makes the study difficult to contain and this may lead to significant attributes of the system being neglected as a whole load of scenes and risks come to light.

<u>**Accounting for disasters**</u>

Thus far the model identifies risks to the system from two main sources both of which can be explained in terms of panarchy. One source of risk is the system/s below the system of concern, and the other is the system/s above the system of concern as shown in Figure 58. The risks generated by the actions within the system of concern are a mix of risks from the levels above and below, as well as risks emerging from the agents interacting within the system of concern. Additionally, there are potential risks from disasters that are not necessarily captured by the product life cycle but are relevant to the system as components of the system and its life cycle may be affected by them. Disasters and disturbances may be a result of emergent behaviour in other systems and can occur in environmental (floods, forest fires, earthquakes, hurricanes, etc.), social or the economic systems without much warning. The emergent behaviours may not necessarily be unknown though they can be unpredictable as they emerge from the different system levels.

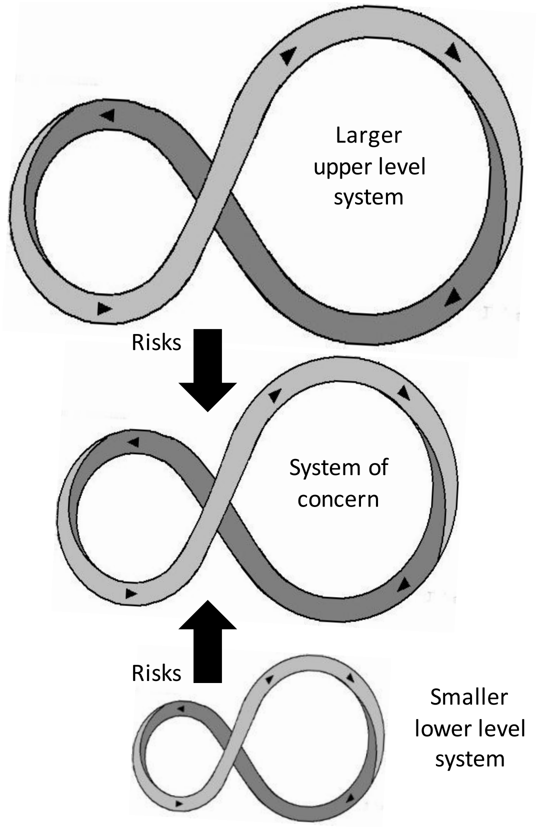

Figure 58: Source of risk to system of concern

An example of how a disaster can affect the product system is the disruption of supplies via loss of components or disruption of component manufacture. For example, the ship that transports components from overseas may run into unexpected bad weather, have an altercation with pirates, have an accident, etc. that results in the loss of its cargo. Another example may concern a specific type of plastic pellet that is manufactured by a supplier located in a zone where forest fires are commonplace. These forest fires may disrupt the operations of the factory itself or the transportation of the pellets if authorities prevent travel to the region. Unlike the former example where disaster strikes leading to loss of components by sea, forest fires are seasonal events and their probability of occurrence increasing with dryness and thus while predictable, they can still be planned for.

Events such as severe storms, floods, storm surges, tornadoes, hurricanes, earthquakes, tsunami, volcanic eruptions, etc. can have significant impact on product systems if the supply chain is affected in some way. In addition to natural disasters, disturbances in the social system can also affect the product system in the short or long term. Social events that could disrupt the product system include elections, political instability and rioting (e.g. rioting and urban violence in France (Koff and Duprez, 2009)), war, epidemic (e.g. smallpox outbreaks (Ferguson et al., 2003)), terrorism (Boscarino et al., 2006), reactions to natural disasters, etc. According to Sidle et al. (2004), "social vulnerability to natural hazards is related to the resources available to cope with the hazard, level of economic development, the ability to predict the occurrence of a hazard and to adjust and adapt to conditions posed by the hazard, and planning measures embraced by societies". Some of the events leading to risks such as those from accidents, natural disasters, social disruptions, etc. could be planned for using experiences from past events.

Disaster risk would be regional and some disasters can be cyclical or the result of seasonal changes (e.g. drought). Awareness of such risks could prevent unsustainability of product systems. Therefore, a generic disaster risk matrix for each location of significant resources, component production, etc. should be developed together with plans for mitigation. Preparedness may assist resilience by assisting the product system to adapt. One such report by the IPCC, a Special Report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" is expected in 2011. Some of the potential disasters that can occur include floods, droughts, forest fires, fires, volcanic eruptions, earthquakes, tsunamis, terrorist attacks, disease epidemics, pandemics, civil unrest, etc.

Dynamic modelling for determining limits and thresholds

As mentioned earlier in this chapter, system behaviour is dynamic and nonlinear. Given that systems are nonlinear, their limits and thresholds are also nonlinear and hence subject to dynamic change. There would be upper and lower limits where breaching the upper limit would result in a regime shift, most probably irreversible, and possibly change the function of the system. It would be beneficial to identify and track dynamic limits such that a practitioner can accurately evaluate risks, giving higher priority to risks that drive the system towards upper limits. However, due to the complex and nonlinear behaviour of systems, it is difficult to determine precise limits. Thus in reality, simulations and projections are used to identify a range of limits that are fuzzy. Given enough historical data, nonlinear behaviour of systems can be modelled and simulated albeit with some uncertainty due to the lack of complete understanding of system behaviour as well as possible emergent properties that are novel in the system. Due to the uncertainty inherent in these models, a number of different scenarios with varying conditions and parameters need to be simulated with risk pertaining to each scenario analysed and evaluated.

Distribution of risk within the social system

Risk events can affect different individuals and different systems in different ways. The model could benefit from analysis of how risks would affect different individuals within the social system according to the locations that are significant for the product system in terms of who is affected and how they are affected. Since the goal of sustainability is about the wellbeing of current and future generations, analysis of how different individuals in different regions cope with effects, their laws, their standards of living, etc. could be beneficial. Projection of their future wellbeing may be modelled with respect to past and present events even though the future may not necessarily happen according to the past. It will however give some indication of how different people in different areas, of different socioeconomic status are expected to fare in the future as a consequence of the product system. This analysis would be speculative at best since the uncertainty with respect to future is great.

7.4 RISK AND SUSTAINABILITY

Risk and sustainability have common ground in that they are both future oriented and related to continuity. Furthermore, evaluating sustainability in terms of risk and managing these risks results in containment of risk that might lead to unsustainability. The main advantage of investigating sustainability from a risk perspective is that depending on the size of the study, vast amounts of information on the system can be obtained. This information may provide decision makers with ample indication of possible future events, affording them almost predictive capabilities to plan and facilitate the direction of future events.

Intuitively, information on possible future risks may allow stakeholder to be better prepared to mitigate negative consequences and take advantage of the opportunities. Management of risk, however, is not conventional for sustainability purposes (Hollnagel et al., 2006) and this is because conventional risk management fails to consider the interconnections among systems. For example, as shown in the previous chapter, risks to the product system are not the only factors that affect sustainability; external (though interconnected) factors from higher level systems also affect the product system. The approach given in this research takes the interconnections into account by basing the RA with the context of complex systems. The remaining section of this chapter is dedicated to discussion regarding the various connections between sustainability and risk with respect to the core concept of sustainability, the impact of risk perception on sustainability, the use of risk knowledge for decision making and finally concluding with the answer to the question of whether risk management can lead to sustainability.

7.4.1 SUSTAINABILITY, CONTINUITY AND COLLAPSE

As discussed in the literature review (Chapter 2), one of the fundamental goals of sustainability is the continuation of the human species where Earth systems need to be healthy and able to support human life. Figure 59 shows the systems that are relevant to sustainability in terms of system dimension and speed of cycles. Risks in each of the CAS in the figure propagate to each other; risks in a lower level system affect the higher levels and vice versa unless they can be mitigated successfully. The faster smaller systems (lower level systems) react faster to risk, specifically operational risks, as the results are almost immediate. Operational risk can be minimised via best practice and following safety procedures. Unfortunately, human error and lack of hindsight plagues the lower level systems and can lead to dire consequences. One such recent event of consequence is the oil well blowout in the Gulf of Mexico (BBC, 2010). According to news reports, numerous mistakes were made during the drilling process creating risks that might have been mitigated had management's priority not focussed on the economic costs.

There are many diverse systems at the product system level and these can impact upon the economic, social and Earth systems. The product systems are also influenced by the economic, social and Earth systems in return. If a product system were to collapse, those likely to be affected include stakeholders such as employees, suppliers, customers, etc. The financial impact is likely to affect the social system where income is tied in with the ability to purchase goods and services to meet basic needs. Furthermore, the larger the product system, the more dependents it would have and hence the greater the impact from its loss. In terms of time, the demise of a product system may affect the economic system until the stakeholders, employees, etc. recover by finding other sources of income. Society would resume normal function unless the product system that collapsed was fundamental for its existence or is not substitutable. For example, if a product system such as an office chair as given in the case study were to collapse, the effect of collapse may include the loss of employment and livelihood for workers leading to social and economic issues; loss of revenue for the company owning the product system; loss of income for stakeholders both internal and external (suppliers, retail outlets, etc.); as well as loss of product diversity. Collapse of the product system may not necessarily lead to the collapse of the business.

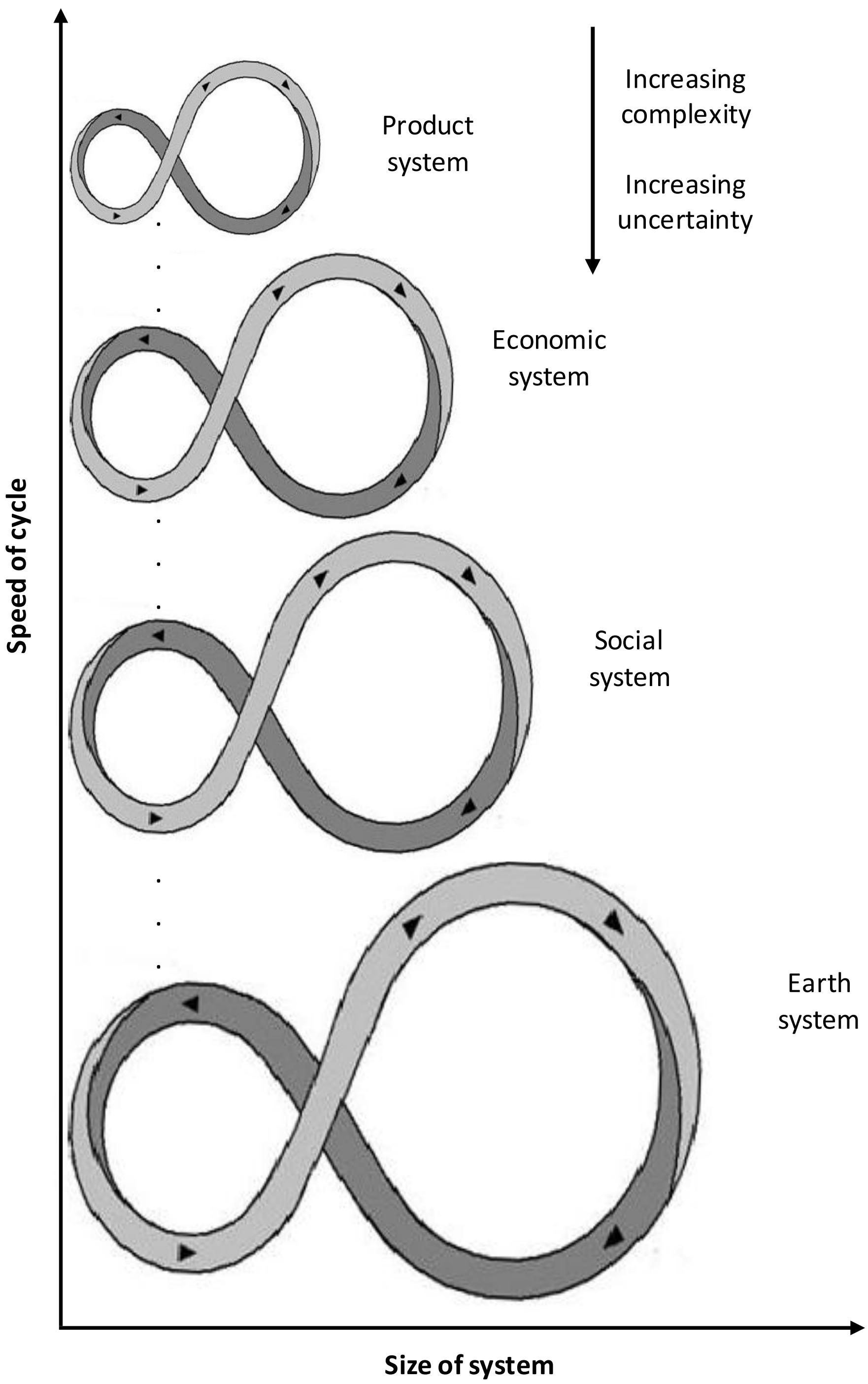

Figure 59: Hierarchy of CAS according to size, cycle speed, complexity and uncertainty (modified using Holling, 2004)

Being forced to discontinue a product due to the collapse of the product system would result in adverse impacts for agents and systems that depend on the product system. However, discontinuance of product is an expected part of a product life cycle (Klepper, 1996; Klepper, 1997). Figure 60 illustrates s-curves corresponding to stages of a product life cycle (PLC): product development, introduction to market, growth, maturity and decline. While there is no empirical evidence to support the existence of a PLC (Michell et al., 1991), and there is criticism regarding the natural nature (birth and death) of products (Dhalla and Yuspeh, 1976; Gardner, 1987), the life cycles of products are said to vary in length and shape (Midgely, 1981). The release and reorganization components of an adaptive cycle (Holling and Gunderson 2002) may apply since the product system is considered to be a CAS. Thus while a product may not last indefinitely, they may evolve with technology. It may be possible to sustain innovation to restart or prolong the product life cycle as shown by "B" in Figure 60 (where "A" is the natural life cycle of the product without undue external influences).

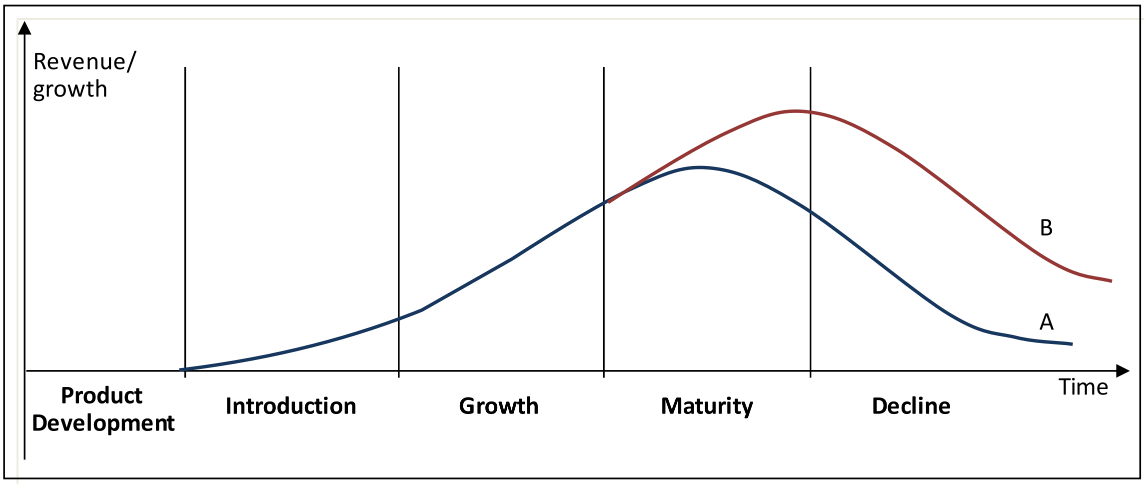

Figure 60: S-curves representing product life cycle stages

Discontinuance or collapse of the product system can occur due to external or internal influences, incremental innovation or radical innovation that replaces the product (Funk, 2008). In the above example, new office furniture products may be designed and manufactured to replace the discontinued product thus sustaining revenue generation and employment. The gradual introduction of new product and discontinuance of old product can be planned for where careful planning may be effective in minimising adverse impacts to the systems of concern. However, abrupt discontinuance due to system collapse may cause adverse effects that cannot be mitigated immediately. The survival of the company (which is essentially a higher level system of the product system) would thus depend on its resilience and ability to adapt to changes that lead to the collapse of the product system.

The product system, through its various interactions and interconnections, would have become a valuable component of the social and economic systems. The collapse of the product system would cause much damage, though eventually, it is possible that the systems may recover and adapt to survive. While the specific office chair system ceases to exist, the basic need for office seating may still exist thus providing opportunity to fulfil the need. Another example of this is the internet which has become a valuable part of communication and social gathering. The possible collapse of the internet would cause much chaos and loss of livelihoods for many. However, the social systems may adapt and find other means of communication and commerce. In the case of internet collapse, social interaction through platforms such as Facebook, Twitter, MySpace, etc. would cease to exist. However, communication as a basic component of the social system would still continue to survive.

The collapse of systems followed by reorganisation is a component of the adaptive cycle. The two examples given also apply to other systems. The impact of system collapse depends on the significance of the system. The significance of the system may be gauged in terms of the need the system fulfils. For example, collapse of systems that deliver water to human population has greater significance than systems that produce goods for leisure, sport, etc. While the loss of these items may not affect the ability to survive, it might deprive happiness and pleasure. If the product system does not provide for a basic need, collapse of the system may not have devastating consequences throughout society even though complexity can make the collapse devastating within parts of the social and economic subsystems. The acceptance of system collapse becomes an ethical concern when comparing the idea of sacrificing the wellbeing of a few to the wellbeing of the majority. In order to overcome this, Krysiak and Krysiak (2006) propose a fairness based criterion to be able to defend acceptable risk for future generations.

The following suppositions can intuitively be made about the nature of the complex systems with respect to sustainability and risk:

- While the goal of sustainability is the continuation of the human species, the continuation of a product system may not necessarily be sustainable if that product system infringes upon the potential for human continuity;
- While the function of a product system may mean the wellbeing of the economic and social systems, if the product system infringes upon the wellbeing of the Earth system, it infringes upon the potential for human continuity; and
- While the function of the product system may infringe upon the potential for human continuity, the product system may be continued given the effort and resources as the function is considered valuable for the human and economic systems.

Given that continuity is not equivalent to sustainability as unsustainable practices can be continued given the effort (e.g. the fossil fuel industry), incentive to discontinue unsustainable practices must come from within the social system. Knowledge of risk to human continuity may be the required incentive. Proliferation of the knowledge of risk events may allow for greater understanding by many which in return means greater consensus for phasing out unsustainable practices and systems. In an ideal world, product systems that cause harmful effects for which mitigation is not possible could be phased out (Figure 61) or alternatives that are less damaging could be found to fulfil the function of the product. However, the reality is that people depend on practices and product systems and unless the risk is affecting them directly, an optimistic view of the world makes them continue with the unsustainable practice and hope for the best.

That is not to say that knowledge of risk events have been ignored completely. Take for example CFC which was widely used by the refrigeration and foam industry. Since a direct link between the CFC and ozone layer depletion was found (Molina and Rowland, 1974), the Montreal Protocol regulated their use and facilitated their phasing out pending 2010. Since the risk of ozone layer depletion was considered a serious threat, their phasing out was possible and alternatives to CFCs were developed. As such, HFCs which have insignificant ozone depletion properties are now utilised (Weigel, 1991; Creazzo and Hammel, 1993). This could be considered as a success story for sustainability as substitutes for the function of CFC were found; and the Earth system is safeguarded from CFC-related ozone depletion. This case is vastly different to that of global warming for three reasons:

1. The function of CFC had viable substitutes;
2. The risk from ozone depletion was taken seriously by decision makers; and
3. The phasing out of CFC does not affect the social system as directly as phasing out practices that cause global warming.

In order to phase out practices that cause global warming, substitutes (for example energy and transport) need to be at hand. Programs to research and develop new cleaner fuels and technologies are underway in many countries where the focus is on finding substitutes to provide for needs while eliminating the adverse consequences such as pollution (e.g. U.S government's programmes for alternate fuel, clean energy, etc (Cormier, 1990; Ogden et al., 2008; DOE, 2010).

While the Kyoto protocol to reduce greenhouse gas emissions was adopted in 1997 and came into effect in 2005, only a few countries are close to achieving target emission reductions. The inactivity, including the United States' refusal to ratify the protocol due to "serious harm to the US economy" as well as the exclusion of developing countries (mainly China) from compliance, means that greenhouse gas emissions are not regulated as CFCs were. Granted that there are some significant issues with the Kyoto Protocol in terms of exemption of developing countries and the time scale for compliance but more importantly, while scientific consensus has been growing, there are still influential naysayers who are adamant that global warming is based on deception, junk science and fraud. While the risks from global warming are known, the problem is extremely complex since it is not simply about the discontinuation of a single chemical substance, but a change in the very way in which we humans live. Thus knowledge of risk events is not sufficient to make changes. Viable substitutes for the function provided by the unsustainable product system, together with consensus regarding the seriousness of the threat and means to minimise the adverse effects of mitigation, are required for action from risk to sustainability.

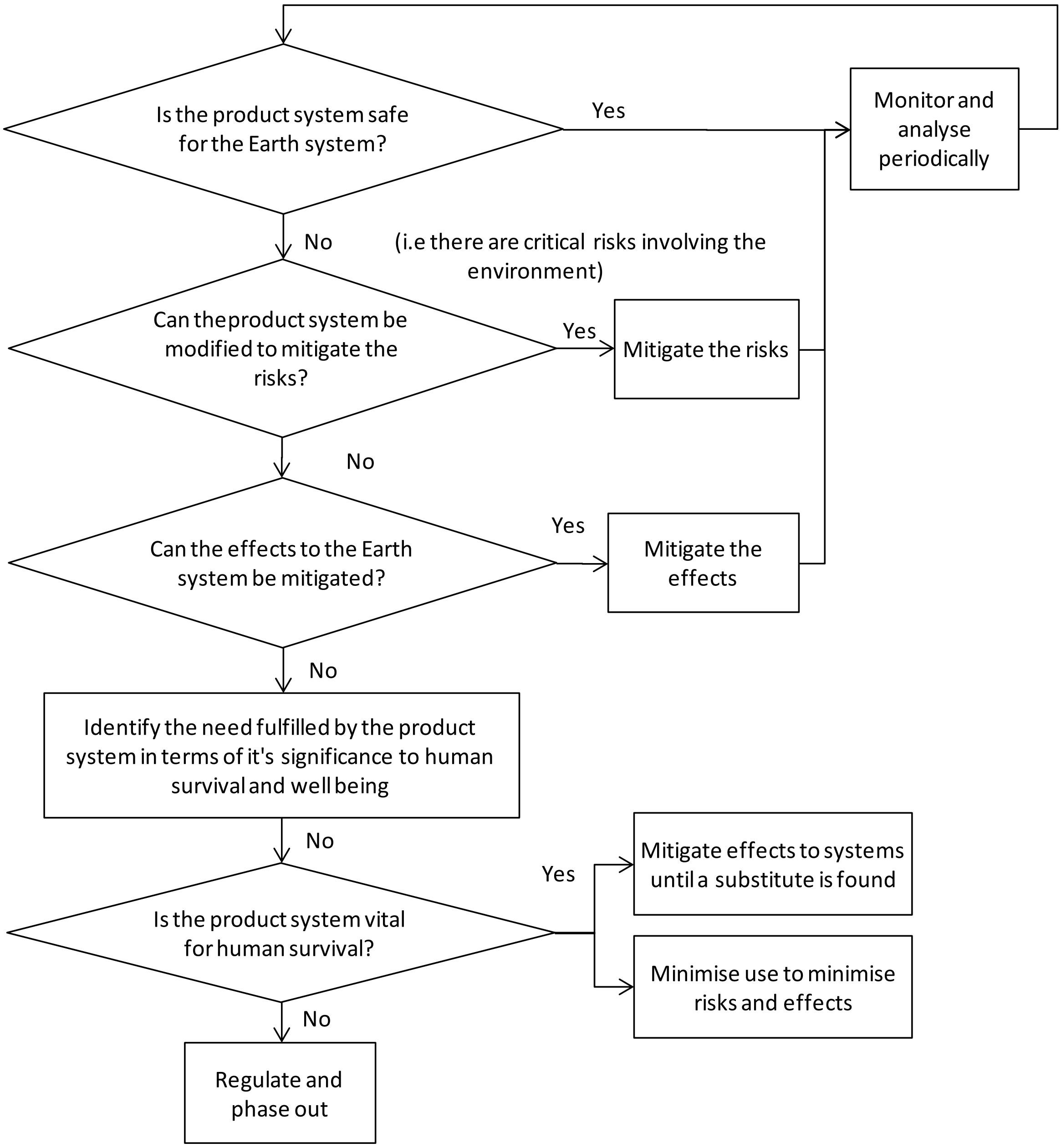

Figure 61: Decisions for sustainability

7.4.2 PERCEPTION OF RISK, NEEDS AND WANTS

Perception of risk is subjective and depends on factors such as gender, race, personal circumstances, culture, background, personality of the individual, etc (Flynn et al., 1994; Renn, 1998; Finucane et al., 2000). Perception of risk plays a significant part in how risks are ranked and therefore, having an incorrect perception of a risk may be as dangerous as being unaware of risks. Perception of risk is influenced by:

- Level of fear or dread regarding a threat;
- Level of control the individual has on the activity related to the threat and whether the activity is by their own choice;
- Whether it is a man-made risk or natural;
- Whether the risk can affect the individual, their property and personal safety;
- Whether the risk affects children;
- Whether the risk event makes headlines and is new (e.g. new disease);
- Awareness of risk – the more awareness, the more perception;
- Whether there is a benefit associated with the risk;
- Whether the risk is associated with a memorable event;
- Whether the risk is spread over time and space; etc.

(Wildavsky and Dake, 1990; Slovic, 1992; Flynn et al., 1994; Fischhoff, 1995; Renn, 1998; Finucane et al., 2000; Rowe and Wright, 2001)

The above influencing factors and the individual's position in Maslow's hierarchy of needs (Maslow, 1968) may help explain the reason for individual perception of risk and how risk awareness may invoke action such as acceptance or mitigation. The theory of needs according to Maslow (1968) has five levels, hierarchically ordered, from physical needs at the base of the pyramid to self-actualisation at the peak as shown in Figure 62.

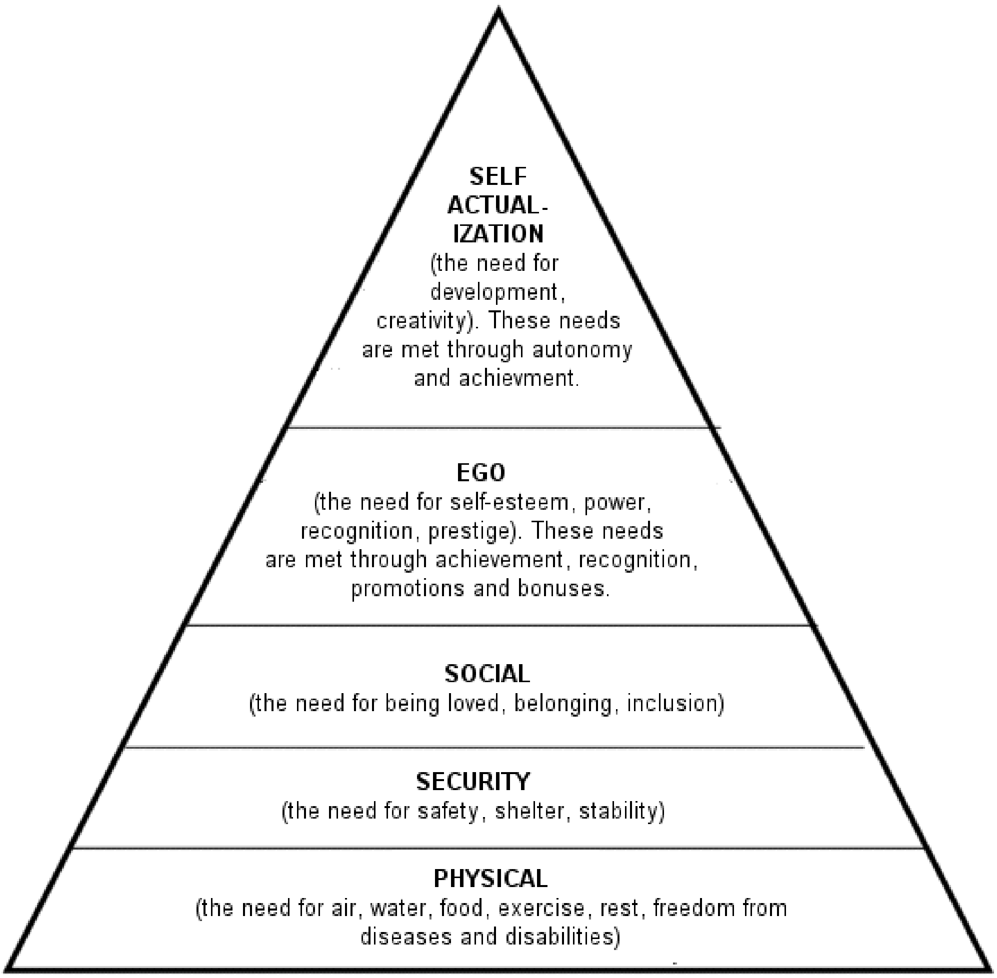

Figure 62: Maslow's hierarchy of needs (Maslow, 1968)

There has been much discourse on the topic of human needs and wants and there is ongoing debate on whether it is in fact possible to discern between the two (Anderton, 2000; Begg et al., 2003). From a consumption point of view, Campbell (1998) states, "the contrast between the two [needs and wants] rests essentially on the distinction between satisfaction and pleasure" thus establishing that needs are essentials while wants are luxuries in line with the Puritan versus Bohemian doctrines (Campbell, 1998). However, to date, there has been no ontological progress in making a substantiated distinction, especially when it comes to the current societal context. Also, there has been much resistance from the economic standpoint that refuses to acknowledge the idea of needs as a fundamental issue, considering them instead as different degrees of mere wants (Galbraith, 1984; Jackson et al., 2004). Additionally, with current levels of globalization and rise of affluence, the line between needs and wants seem to be blurring rapidly. As such, some of the previous generations' wants can now be accounted as the new generations' needs. Thus there is a dynamic element to human needs with respect to technological developments and therefore new generations are unlikely to accept just the basic needs for survival as their needs. This makes the discussion of needs in terms of the basics as well as the evolved technological requirements, complex yet fundamental to providing insight for future concerns including risk perception and how individuals react to risk awareness.

Human beings are complex conscious beings whose requirements for life include not only the basic inputs for physiological survival but also satisfiers for psychological wellbeing where the inability to satisfy a need is considered a form of poverty (Maslow, 1954; Max-Neef, 1992; Peet and Bossel, 2000). An individual would focus on their current level of needs and as such a person who is suffering a certain type of poverty would focus on relieving that particular poverty. This means that they are either unaware of or do not acknowledge certain types of risks that fall outside their focus of needs; or they are aware and yet perceive the risk as acceptable since they are more concerned about overcoming the current poverty which is perceived to be of greater risk.

One of the ways in which to overcome issues with different perceptions of risks has been to engage experts. However, according to Ball (2002), perception of risk, even by experts, can be biased. Ball (2002) argues that experts are as equally biased as lay people. Thus while experts may be knowledgeable in terms of identifying risks, they may not be suitable for evaluating and ranking them since they themselves would have needs on which they are focussed and thus unconsciously biased. To counter personal agendas and bias, data can be gathered by large groups of experts and laymen and is one recommendation in improving the current model at the evaluation stage. It is not clear whether humanity drives the socioeconomic system, or whether the socioeconomic system drives humanity. Nevertheless, humanity's focus on satisfaction of needs, social relativism, consumerism, materialism (Babarenda Gamage and Boyle, 2008), etc. results in unsustainable practices, where unsustainable product systems exist and function despite the risks involved.

7.4.3 SOCIAL CONTEXTS AND BARRIERS TO RISK UNDERSTANDING

Knowing about the risks involved with any action should make the stakeholders, those likely to be affected, cautious. Ideally, they should then attempt to mitigate the risks to safeguard themselves. Likewise, for a product system, the knowledge of the risk, the mitigation procedure and the results of mitigation should feed back into the cycle to improve the product system. Figure 63 illustrates the pathways for the use of knowledge where the assessment of the product system leads to knowledge of risks and action for mitigation which needs to be fed into the human system such that changes may be made at the level of needs. Furthermore, if the risks are deemed to be extreme, then mitigation wouldn't be enough. Changing the product system or phasing it out in favour of one that fulfils the function or need of the product and contains less risk would have beneficial consequences. However, the complex nature of human needs (including psychological), the greater social system, the economic system, etc. and the way they interact with each other makes it such that knowing about the risks is not sufficient for sustainability. The reason for this is that risk awareness does not necessarily mean that risk mitigation will be carried out. However, if means for mitigation are available and the risks are mitigated, certain unsustainable practices may be eliminated from the system.

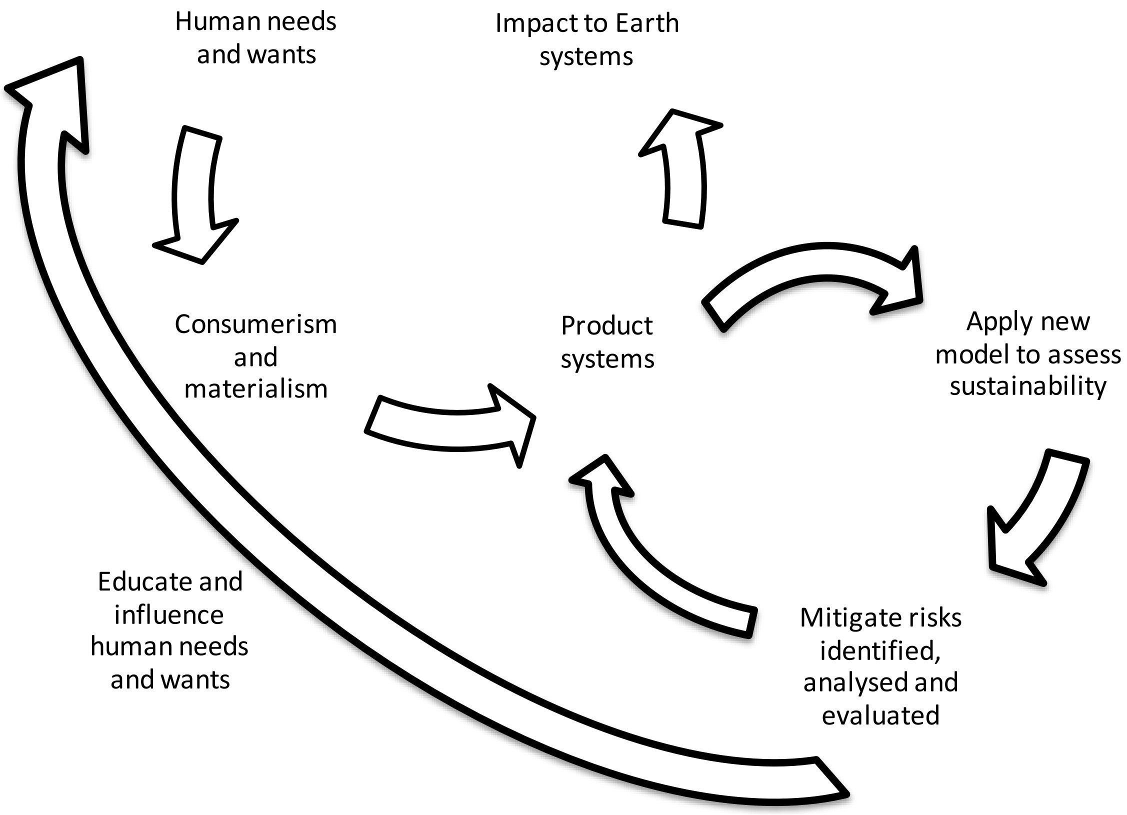

Figure 63: Knowledge pathways required to move from risk to sustainability

The issue though is that removing unsustainability via mitigating known risks may not necessarily mean sustainability of the system because there could be unknown risks that could surface at any given time. If there are no unknown risks, which is unlikely in the real world, then the system could be sustainable. Removing risk events that may inhibit continuity would help prolong the function of the system via improvements to the product system thus sustainability in terms of continuity can be achieved if all risk events are mitigated (Figure 64). In reality, not all risks can be identified and additionally, due to the complex and dynamic nature of the systems, it is likely that new risks are generated with changes in the systems.

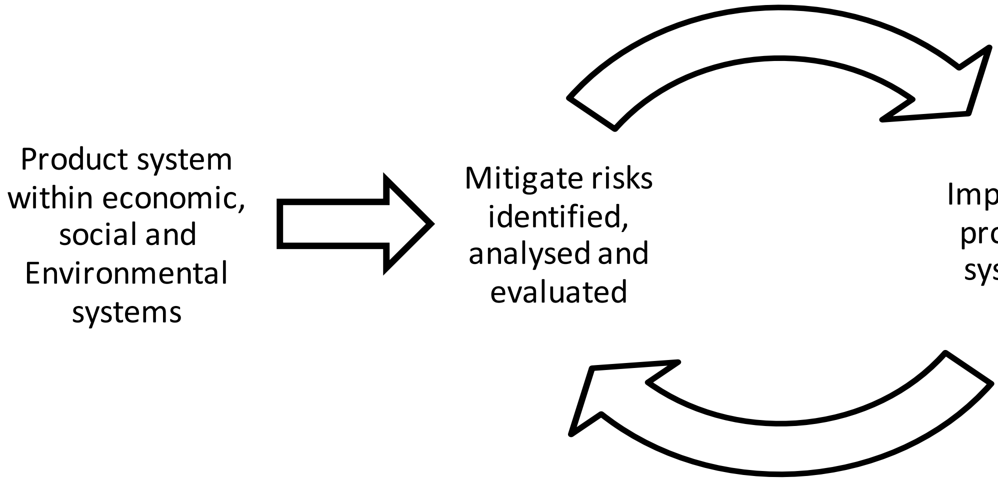

Figure 64: Continuation of the system via risk mitigation

If relevant critical risks in the complex system are identified, and the critical risks are mitigated, then since there is nothing to hinder continuity of the system, the system could be sustained. However, active identification of risks and mitigation would be required as an ongoing process in order to determine new risks. If mistakes are made and a risk that is deemed to be critical is not mitigated, then the reaction to the risk event actualising could lead to the demise of the system. The uncertain nature of the future leaves no guarantee for sustainability. Furthermore, mitigation of risk is only successful depending on how the risks are evaluated. The decision on whether a possible risk is worthy of being mitigated, or accepted, is at the heart of the issue and this is directly related to the ways in which individuals perceive risk. If a critical risk was accepted rather than mitigated, the system would be adversely affected and unsustainable.

Barriers to risk understanding may prevent action to treat risks thus leading to acceptance of risks that should be mitigated. Examples of barriers to risk communication and understanding include: lack of trust in risk information or the source of risk information; influences from media where selective reporting confuses the risk information; confusing or incomplete risk messages; psychological factors (risk perception, personality characteristics, and psychological states, etc.); and social factors (Covello and Wolf, 2003). Additionally, individuals face different types of risks, sometimes multiple risks at any given time. The vastness of risk information from multiple sources can hinder understanding of risk (Harris and Smith, 2005). Furthermore, understanding of risk does not necessarily mean that society will act upon the information. According to

Chaiken et al. (1989), cognitive psychology and neuroscience theories show that human beings understand risk by two means:

1. Analytical system e.g. using risk assessment, probability, etc.; and
2. Experiential system controlled by conscious awareness.

Huang et al. (2010) states that "the rational analytic and experiential systems operate in parallel, and each seems to depend on the other for guidance." Emotion plays a significant role in risk acceptance as the experiential system is faster to acknowledge and relate to risk (i.e. it depends on how an individual feels about a risk). The potential opportunities associated with overcoming the risk event are another reason for risk acceptance. I.e. if an individual likes an activity and they benefit from it, they tend to downplay the risk (Slovic et al., 2004; Smith, 2008). This could explain the acceptance of risk such as living in areas prone to hazards (e.g. Auckland volcanic field) or having high risk occupations (e.g. armed forces). Individuals are able to make their own decisions based on their intuition or analysis of a given situation. However, it becomes an ethical concern when decision makers accept risks on behalf of components of the social and environmental systems.

7.5 CHAPTER CONCLUSIONS

This chapter contained a critique of the new model for assessing sustainability of complex systems including an account of how the model contains elements of complex system criteria for sustainability that were identified in Chapter 3. The discussion progresses to the deficiencies of the model in terms of uncertainty and the ways with which to overcome some of the uncertainty. The need for dynamic modelling, accounting of external risks, accounting for the socioeconomic status in which the product system exists, etc. are some ways of improving the model. Additionally, it was found that a model for assessing sustainability with respect to risk needs to take into account three different yet interconnected levels of risk:

1. Risks from the micro level or risks within the product system;
2. Risks at the macro level where the risks to the other systems can cause risks across systems; and
3. External risks from random disasters and events that are common to the regions the product system is associated with – resulting from emergence.

The model was able to contain the first and the second type of risk with the third being a means of improving the model. The first two types of risk are connected as they occur across the system levels of concern. The interconnections and interdependencies among the systems, their ability to co-evolve in response to changes that emerge from the interaction of individual agents within each system means that risks should be mitigated cautiously so as to avoid transfer of risks across systems.

The research gives an insight to the various perspectives of sustainability as constructs based on continuity and how mitigating risks may lead to sustainability by the removal of events that can cause unsustainability. The relationship between the product system, the function it provides with respect to the hierarchy of needs show that risk awareness and risk mitigation needs to be coupled with education and changes with respect to human needs. Together, changes in the needs and how these needs are met plus mitigation of risk across system levels could pave the way for sustainability. Risk awareness would be beneficial if the risks are evaluated accurately with ample awareness of complexities within and across different system levels.

CHAPTER 8: CONCLUSIONS AND FUTURE WORK

The primary objective of this thesis was to develop a new model to assess sustainability of complex systems where the motivation stemmed from the need to practically implement principles of sustainability. The foundation of the new model presented here draws from literature based on complex systems theory and theory on sustainability. The theory on sustainability includes work based on existing sustainability assessment method and models. The primary objective of this thesis was fulfilled via three sub-objectives:

1. Review existing models and methods to determine if they assess sustainability;
    - Determine the basic criteria required for sustainability and hence determine whether the existing methods and models assess sustainability;
    - Determine what methods and models exist for assessing sustainability and identify strengths and weaknesses of the existing methods and models;
    - Evaluate the existing methods and models to determine if they are able to assess sustainability of complex systems;
2. Develop a new model to assess sustainability by integrating existing methods and models;
    - Integrate the most appropriate existing models so as to capitalise on their strengths, minimise individual weaknesses and also meet the criteria for sustainability; and
3. Test the new model on case studies;
    - Use the new model to assess systems within business to determine whether the model can practically assess sustainability.

The conclusions drawn from each sub-objective, and the thesis as a whole, are given as follows.

8.1 SUB-OBJECTIVE 1

The first sub-objective was to review complex systems theory and existing sustainability assessment methods and models to determine whether they were capable of assessing complex systems such as human and Earth systems. From the review of literature, it was concluded that human and Earth systems are complex systems. More specifically, human and Earth systems are complex adaptive systems (CAS). CAS are systems made up of multiple diverse agents exhibiting a multitude of complex system characteristics such as: connectedness, nestedness, nonlinearity, no absolute boundaries and controllers, existing within limits, feedback loops, memory, self-organisation, emergence, co-evolution, ability to adapt and be resilient, etc.

From the characteristics of complex systems, criteria required for assessing sustainability were identified as follows:

1. Take complexity of the system into account by:
    a. Recognising the existence of multiple agents and system levels;
    b. Recognising interconnections and interdependencies;
    c. Taking system dynamics into account (time and space);
    d. Recognising system limits or thresholds;
    e. Recognising resilience and adaptive capacity; and
    f. Being holistic; and
2. Be based on science where appropriate.

Criteria pertaining to multiple agents/systems, dynamics, interconnections and interdependencies, limits, resilience, and holistic nature were deemed to be significant for complex systems. Therefore, it was concluded that they should be analysed or accounted for during sustainability assessment. An additional criterion regarding the scientific nature of the method was also included so as to determine whether the methods/models are based on sound science with vigorous scientific methodology.

The criteria were used to evaluate 26 existing sustainability assessment methods and models. These methods consist of analytical tools (e.g. cost benefit analysis, etc.), indicator based methods (e.g. Living Planet Index, Well Being Index, etc.) and integrated methods (Ecological Footprint, triple bottom line (TBL), etc.). The evaluation was aimed at determining whether existing methods and models are able to assess CAS, and to identify methods and models that are able to take into account some of the characteristics of CAS. The evaluation leads to two conclusions:

1. While the existing methods and models were successful in achieving their respective goals for which they were developed, the methods did not take into account key criteria pertaining to complex systems. This means that the existing methods and models are not suitable of assessing sustainability of complex systems; and
2. Eight methods that contained elements of identified criteria required for assessing sustainability of complex systems were found. These methods include: risk assessment (RA) (analytical tool); ecosystem resilience (integrated method); Sustainable Process Index (an indicator); Life Cycle Assessment (LCA) (analytical tool); Product Sustainability Index (an indicator); Ecological Footprint (integrated method); Barometer of Sustainability (integrated method); and Sustainability Assessment by Fuzzy Evaluation (SAFE) (integrated method).

Generally, all of the identified methods and models may be integrated together in some way. Some of these methods may simply be extended in terms of their boundaries and scope to enable them to include characteristics of complex systems that are just beyond their reach. For example, LCA may be extended to include broader social/cultural dimensions such as community and economics to be analysed thus improving its abilities in terms of becoming a more holistic tool. Choosing the most appropriate methods for integrating was based on whether:

- The assessment methods have been standardised;
- The assessment methods have readily available literature as guides;
- The assessment methods are used for education, planning and policy development;
- Databases for the assessment methods exist;
- Research with respect to the assessment method have their own academic journals (i.e. indicating whether there is high volume of research in progress);
- The assessment methods and their results are widely communicated and accepted;
- The assessment methods comprise of the necessary characteristics to be integrated with RA (i.e. if there have been previous attempts to integrate); and
- The assessment methods complement each other.

Exploration and evaluation of the methods concluded with two key methods, LCA and RA, that contained the elements sought for assessing sustainability of complex systems. LCA and RA were thus chosen as components of the new model.

8.2 SUB-OBJECTIVE 2

The thesis fulfilled the second sub-objective by integrating LCA and RA in a practical manner. Since LCA and RA have previously been integrated, the previous work was reviewed to identify methods and reasons for integrations. It was found that the two methods were integrated not for the purpose of sustainability assessment, but to relieve each method of select deficiencies. For example, integration of RA into LCA was expected to introduce spatial resolution to LCA thereby improving LCA. Some of the ways in which LCA and RA can be integrated are by separately conducting LCA and RA and integrating the results; iterative use of LCA and RA where the results are either in terms of environmental impacts or in terms of risks; incorporation of lifecycle thinking into the RA framework in order to better relate risk to policy; incorporating risk into the LCA framework for spatial differentiation; use of process chains rather than the use of all process units for a given functional unit and thus reducing scope and allowing more detailed assessment; and limiting of system boundaries such that RA and LCA boundaries are identical.

The final model presented in this thesis is a hybrid model, beginning with LCA and concluding with RA where the two methods integrate at the impact assessment step of LCA. The basic framework for the new model is given in Figure 65. Since LCA and RA have both been standardized, the standards (ISO 14040, ISO 14044, AS-NZS 4360-2004, ISO/IEC 31010:2009) together with handbooks (Guinée et al., 2002; Baumann and Tillman, 2004; etc.) can provide information and guidance on some of the elements to be addressed for parts of this model.

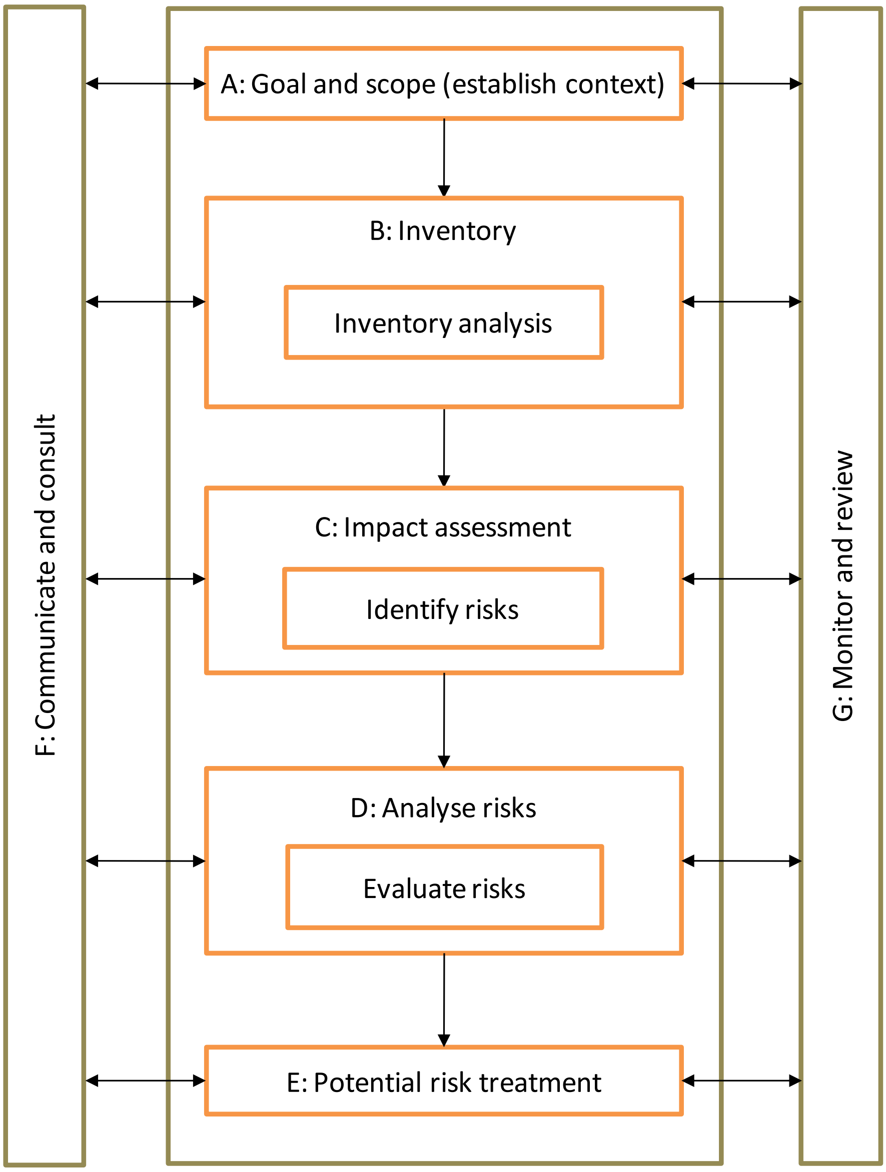

Figure 65: Sustainability assessment framework integrating LCA and RA

The LCA is used to obtain the inventory, a compilation of the needs (resources) and the outputs of the system being assessed. The locations from where the resources are taken as well as where processing takes place is noted along the life cycle of the product. An impact assessment methodology using multiple system impact assessments categories (environmental, social and economical) are to be used in the impact assessment step. The impact categories serve to enable identification of risk to the higher level systems which are able to affect the product system. The impact assessment results in the identification of hotspots during the life cycle. These hotspots are analysed with respect to the material, origin, type of impact, etc. and risks from these hotspots are identified and analysed to highlight events that may affect the product system contributed from the lower level systems as well as within the product system. While the hotspots can identify the weakest areas of the life cycle, analysing all inventory data is required to identify risks throughout the whole system though that would be time and resource intensive.

There are many RA methods that can be utilised for assessing risk. The choice of RA method to use in this model is left up to the practitioner where the chosen method depends on factors such as how well risks can be identified using the method, whether it considers consequence, probability, is able to evaluate risks according to level of risk, the data requirement, degree of uncertainty, complexity and whether a qualitative or quantitative approach is desired. Once the identified risks are analysed according to probability and consequence, they are evaluated and ranked according to the nature of the risk in terms of how critical they are. Risks that could cause system regime shifts are prioritised and designated for mitigation, a type of risk treatment. Lower level risks are to be controlled and/or accepted.

8.3 SUB-OBJECTIVE 3

The third sub-objective of the thesis was achieved by testing the new model on a case study product. A number of case studies were conducted to test the application of the model in a small/medium sized enterprise (SME). The process of implementation as well as the results of one product system, that of an office chair, were presented to illustrate the phases of the new model and its practical abilities. Data were gathered from suppliers via questionnaires and used in conjunction with existing data records for processes within the life cycle. All life cycle stages from raw material extraction and refining of materials to waste management at end of life were included. The LCA impact assessment was carried out using CML baseline 2000 in SimaPro6. The impact categories used to assess the product lifecycle include global warming potential (GWP 100), abiotic depletion, ozone layer depletion (ODP), human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication. In-depth analysis was conducted on the global warming impact potential category for two reasons:

1. The results of the other impact category are consistent with that of the GWP category during the life cycle stages; and
2. GWP represents one of the significant global concerns of our time.

The case study on the office chair showed consistent results to that of the other products on which the model was applied thus illustrating the model's transferability for use by any other product system. It was found that one of the significant hotspots of the life cycle is the raw material extraction and refinement stage where high energy intensive materials such as aluminium lead to high impact. Fossil fuels were also a significant contributing factor of impact across all impact categories due to its use for combustion and heating. Investigating each stage of the lifecycle reveals the impact contributing resources and processes where the RA phase identifies and evaluates the risks involved.

The model results in two forms of risk or threat identification and since a risk matrix method was used for to evaluate risk for the case study systems, two risk matrices result. The first risk matrix identifies risks associated with the impact categories used for LCA. These are essentially the impacts and risks from the product system that affect the higher level systems. They are significant because impacts upon the higher level systems ultimately affect the product system as a result of co-evolution. The second risk matrix determines how the lower level systems, i.e. suppliers of resource and utility, would affect the product system. In this case the RA was carried out with respect to determining threats to the continuation of the product system via risk from the lower levels. Each risk matrix consists of evaluated risk where the risks are ranked according to how critical they are.

The case studies for this research can be considered as streamlined cases, since not all avenues and all inventory data were individually examined. Only those of high significance, for example aluminium, steel, fossil fuel for energy and plastics, etc. were discussed in terms of the risks to the product system and through the product system to the Earth system. This highlights a potential limitation though it is a practical limitation with respect to terms of time and resource requirements. The model was found to be data intensive and unless the data are readily available, it can also be time intensive to gather. In order to overcome these two issues, centralized databases per region and if possible per locale or sector are recommended for future work. This would only require some improvement to the currently existing databases such as EcoInvent where each data record needs to be updated in terms of potential effects to the social and economic systems, the specific location of inputs and outputs, etc. For a full and complete assessment, each and every one of the inputs and outputs of the system needs to be analysed and a full mode assessment is possible with adequate data and time. As with many other models the output of the model is highly dependent on the data input.

Once the risks from both matrices are mitigated, the model is reiterated using new data from new events or the reactions to the mitigation action. This can be done until all critical risks are mitigated and are considered to be an ongoing process. It is unlikely that there would come a time when all risks are mitigated simply due to the nature of complex systems. The dynamic nature of systems coupled with their nonlinear nature, multiple agents interdependencies and interconnections would mean that the systems are changing, either evolving on their own or as a direct result of changes made to the system. This would mean that new risks are generated with time and thus need to be identified and mitigated proactively. It is concluded that the model needs to be reiterated in order to track changes occurring within the product system as well as across the different system levels.

8.4 RISK TREATMENT AND SUSTAINABILITY

Further to the development and implementation of the model, the concept of risk as a means for sustainability was explored where mitigation of risk may be the key to sustainability. The sustainability of a system such as a product system relies on meeting the needs of the system internally. However, external events that affect the function of the system are also critical for its continuance. The risks to a system's needs come from the system levels below as well as those above it are best described and illustrated by the concept of panarchy. If these risks are mitigated, the product system may be able to continue indefinitely. However, continuance of a product system may be forced via manipulation of the lower and upper level systems. If the product system impacts adversely on the Earth systems irrespective of the mitigations or as an indirect result of mitigation, the overall effect is unsustainability. The interconnections and interdependencies in the systems may be able to shift and absorb the impacts until such time that limits or thresholds are breached and systems shift regimes as a result. While a product system may be able to function for extended periods even with adverse effects on the Earth systems, damage to higher level systems are likely to affect the product system eventually. As such, phasing out damaging product systems may be necessary for the future wellbeing of Earth systems and ultimately beneficial for human survival. However, phasing out of an economically and socially valued product system depends upon how critical the function is to the needs of society, whether function of the product system can be substituted for by another product; whether the impact of the product system is perceived to be unacceptably critical. Where there are no substitutes for the function of a product system, mitigation of risk may assist to prevent undue damage while substitutes are actively sought.

One of the significant findings of the research include three different though interconnected levels of risk that need to be mitigated in order to assist the continuance of the system of concern (in this case a product system), keeping in mind that the goal of sustainability is the continuance of the human species. The three levels of risks are (Figure 66):

1. Risks from smaller lower level systems (micro level) - risks within the product system as well as risks to the product system from systems below;
2. Risks from the larger upper level systems (macro level); and
3. External risks from random disasters – risks from emergence.

Risk awareness and mitigation would be most beneficial if the risks are evaluated accurately with ample awareness of complexities within and across different system levels.

There are some significant issues with respect to accuracy and uncertainty regarding risk. Risks are evaluated using information obtained from either laymen or experts, human beings who are subject to bias according to many factors including their own awareness of the risks, gender, age, and most specifically their focus on their individual needs at the time. Bias in risk evaluation may lead to mistakes in risk evaluation and ranking. This ultimately means that risks that should be mitigated could instead be accepted and vice versa. The inability to mitigate a risk that is critical to the system's wellbeing could very well mean the collapse of the system. There are also ethical issues with respect to the choice of risks deemed to be acceptable. These risk events need to be thoroughly analysed in order to evaluate the potential risk of accepting certain risks. Moreover, having mitigated a critical risk could result in overconfidence and as a consequence certain risks may be overlooked.

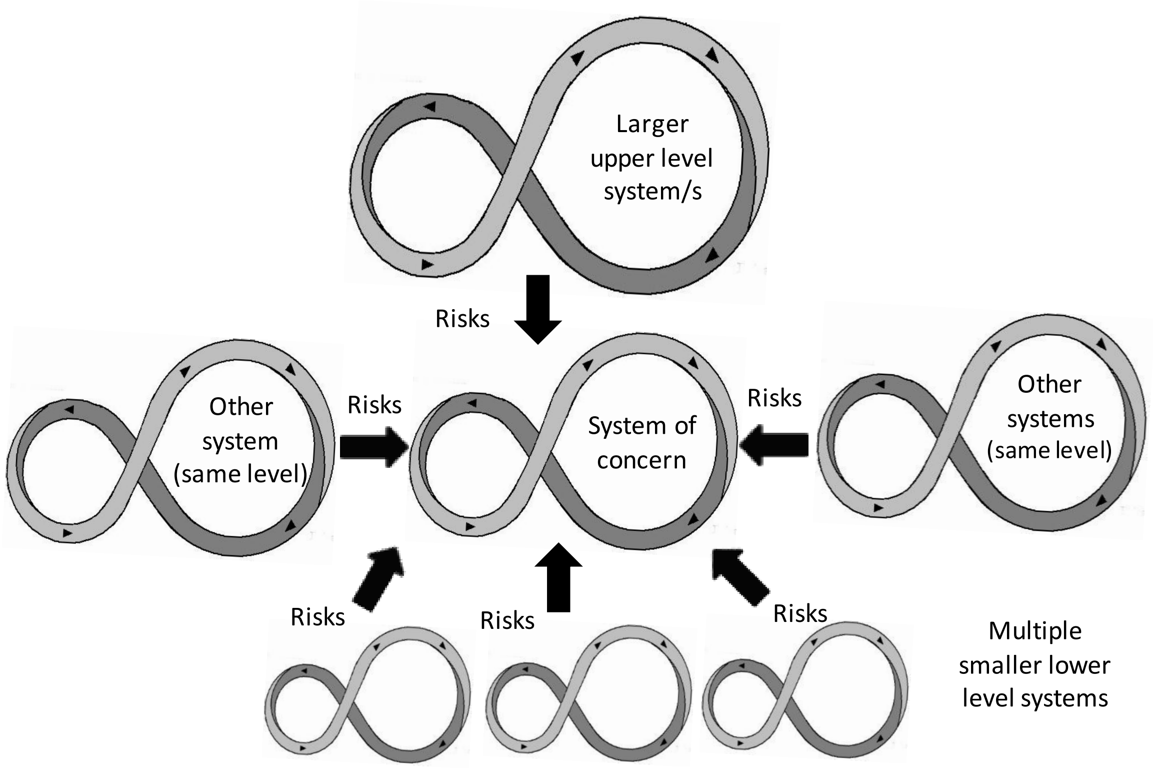

Figure 66: Source of risk to system of concern

The uncertainty regarding risk is mostly concerned with the unknowns related to future events where uncertainty increases with temporal distance. In order to overcome some of these issues, participation of numerous experts for risk ranking, as well as modelling and simulation for different possible future scenarios should be included in future work. Furthermore, the relationship between the product system and the function it provides with respect to the hierarchy of needs shows that risk awareness and risk mitigation need to be coupled with education and changes with respect to human needs if sustainability is to become a reality.

Overall, information on risk and mitigation efforts could ultimately help increase the resilience of the system and even if the risk events do not materialise, the knowledge created in implementing the model could be of use to further understanding of how complex systems function.

8.5 CRITIQUE OF THE RESEARCH AND FUTURE WORK

While there were some limitations with respect to the implementation of the model, these limitations are concerned with practical implementation rather than issues with the model itself. For example, the application of the model brought a number of deficiencies to light. This in turn enabled exploration of how to improve the model's implementation with future work. There were two major issues identified via case study implementation of the model:

1. The model was tested using environmental input as the primary source of data. This means that the inventory step where data on inputs and outputs are collected could be improved by incorporating social and economic inputs and outputs per record as recommended for the model. This would initiate the integration of the environmental, social and economic systems as shown in Figure 67. Location of inputs and outputs, etc. in one single interconnected record would lead to more information about the system; and
2. Social and economic impact categories should be added to the existing impact category sets such that impact assessment is also encompassed in one set. These impact categories should be differentiated with respect to time, automatically assigning different levels of impact for different time scales. Figure 67 illustrates the addition of social and economic impacts at the second stage of the model.

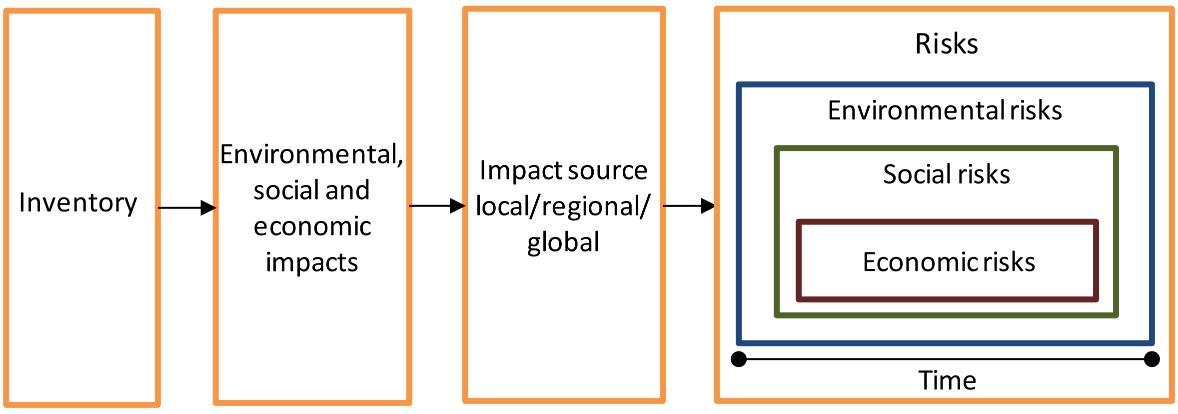

Figure 67: Complete sustainability assessment

8.5.1 CRITIQUE OF THE MODEL

The model is robust owing to components of the model that have seen much improvement and research over the years. However, there are some areas where the model could be improved though most of these require improvement and research in other fields:

- Unknowns are a significant issue with any model and in this case the uncertainties with respect to possible future events increase with the timescale that is considered. While the model is able to identify risks, there are bound to be limitless unknown risks with unknown consequences. Participation of a wide range of stakeholders and experts may be required for get more information revealing the complex interconnections and interdependencies within systems;
- The model focuses mainly on risk which needs to be treated by a range of actions including accepting and mitigating. Where there is opportunity to investigate the benefits associated with risk, the model does not have a formal stage where benefits are analysed. Investigating the benefits associated with threats could be useful for sustainability of complex systems;
- The analysis for the case study is based on a future that is much like the present. The future may not be like the present and hence taking possible futures into account and modelling different scenarios and the risks they present to sustainability of systems could be a beneficial part of the model;
- Considering that systems are dynamic, a significant component that could be added to the model is dynamic modelling of systems and events;
- While accounting for disasters and distribution of risk is part of the model to some extent, the model needs to make the interconnections among events more explicitly. This would require greater participation and more data.

8.5.2 FUTURE WORK

In-depth quantified risk results where chemicals, toxicity characteristics, cancer risks, pollutant emissions to air, water and soils, etc. are outlined per product system is bound to add value to the model. Future work with respect to the RA stage of the model may also focus on reducing uncertainty and increasing accuracy. Accuracy may be increased by selecting appropriate RA methods according to data availability and goal of the assessment. The risk evaluation step could be improved by dynamic modelling of systems to identify system limits; collecting appropriate data from risk experts; and carrying out the risk analysis within different potential socioeconomic climates. Implementing the model within various system parameters and conditions may allow understanding of worst case and best case scenarios for the future. Furthermore, while the model is expected to be transferable to other product systems, future research could test the model further by either using different product systems or different system levels.

This research also leads to a number of questions, one of which is only partly answered here. The main question is, “Would management of risk lead to sustainability?” The answer from this research is that risk management could lead to sustainability if the following conditions are met:

1. The assessment utilizes data from across different system levels;
2. The assessment is reiterated to provide information for sound decision making;
3. The risks are accurately evaluated together with the modelling and simulation of future scenarios;
4. All inventory inputs and outputs are analyzed and risks from each are mitigated;
5. Modelling of systems lead to accurate indication of system limits or thresholds;
6. Risks are evaluated with high degree of accuracy with expert knowledge from different sectors, demographics, etc.
7. Accepted risks are evaluated in terms of whether they are ethically acceptable;
8. Appropriate mitigation is carried out and the model reiterated to constantly find and mitigate critical risks;
9. The knowledge from the assessment and mitigation are fed back into the social systems such that education regarding the risks and their complexity are understood by a wider audience; and
10. A centralized system of knowledge and data are available for use in decision making.

Future work could involve testing out any of the above. Thus the hypothesis that “mitigating risk to complex systems would result in system sustainability” could be a significant contribution to future research in the field.

REFERENCES

Aall C., Norland I.T. (2005) The use of the ecological footprint in local politics and administration: Results and implications from Norway Local Environment, 10 (2), pp. 159-172.

Abel N., Cumming D.H.M., Anderies J.M. (2006) Collapse and reorganization in social-ecological systems: Question, some ideas, and policy implications, Ecology and Society, 11 (1), art. no. 17

Abell, B (1997) Extending ideas about Complex Adaptive Systems into the world of business, Presentation at Santa Fe Centre for Emergent Strategies. Santa Fe, New Mexico

Adams, C., Frost, G. and Webber, W. 2004. Triple Bottom Line: A review of the literature. in Adrian Henriques and Julie Richardson (eds) The Triple Bottom Line: does it all add up. EarthScan: London UK.

Adger, W.N. (2006) Vulnerability. Global Environmental Change 16 (3), 268–281.

Alexander, D. (2000) Confronting Catastrophe: New Perspectives on Natural Disasters, Terra Publishing, Harpenden, England.

Alexandros Gasparatos, A., El-Haram, M. And M. Horner (2008) A critical review of reductionist approaches for assessing the progress towards sustainability, Environmental Impact Assessment Review 28: 286–311

Allison, H. E. and R. J. Hobbs (2004) Resilience, adaptive capacity, and the “Lock-in Trap” of the Western Australian agricultural region. Ecology and Society 9(1): 3. [online] URL: http://www.ecologyandsociety.org/vol9/iss1/art3/

Anastas, P. and J. Zimmerman (2003). "Design through the Twelve Principles of Green Engineering." Environmental Science and Technology 37(5): 94A-101A.

Anderle, K. (2002) Integrating life cycle analysis and the ecological footprint calculator to foster sustainable behaviours, Master of Science Thesis, University of North Texas

Anderson, D. (2003) ‘Fairness in the face of conflict: dividing environmental assets and obligations’, International Journal of Sustainable Development, Vol. 3, No. 2, pp.116–132.

Anderson, P. (1999) ‘‘Complexity theory and organization science’’, Organization Science, Vol. 10 No. 3,pp. 216-32.

Andersson, B., Azat, C., Holmberg, J. And Karlsson, S. (1998) Materials constraints in a global energy scenario based on thin-film solar cells, Energy: The International Journal, 23:407-411

Anderton, A 2000. Economics (3rd edition), Ormskirk, UK: Causeway Press.

Andriantiatsaholiniaina L.A., Kouikoglou V.S., Phillis Y.A. (2004) Evaluating strategies for sustainable development: Fuzzy logic reasoning and sensitivity analysis, Ecological Economics, 48 (2), pp. 149-172.

Arrow K. (1995) Economic growth, carrying capacity, and the environment, Ecological Economics, 15 (2), pp. 91-95.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Janssen, S. Levin, K.-. Mäler, C. Perrings, and D. Pimentel. (1995) Economic growth, carrying capacity, and the environment, Science, 268: 520-521.

Arthur, B. (1995) Complexity in Economics and Financial Markets, Complexity (1), 20-25. www.santafe.edu/arthur/Papers/Pdf_files/Complexity_Jnl.pdf

Arthur, W., B. (1996) Increasing returns and the new world of business, Harvard Business Review, July-August 1996, 74(4): 100-109

Arthur, W., B. (1997) Introduction: Process and Emergence in the Economy . In: The Economy as an Evolving Complex System II, eds. W. Brian Arthur, Steven Durlauf, and David A. Lane. Reading, Mass, USA: Addison-Wesley Pub. Co, 1997.pp. 1-04

AS/NZS 4360: 2004 Risk Management standards

Ascher W. (2001) Coping with complexity and organizational interests in natural resource management, Ecosystems, 4 (8), pp. 742-757.

Ayres, R., van der Bergh, J. and Gowdy, J. (2001) 'Strong versus weak sustainability: economics, natural sciences, and "consilience"', Environmental Ethics, Vol. 23, No. 2, pp.155–168.

Ayres, R.U. (1995) Life cycle analysis: A critique, Resources, Conservation and Recycling, 14 (3-4), pp. 199-223.

Azapagic A, and Clift R. (1999) Allocation of environmental burdens in multiplefunction systems. J Clean Prod; 7:101– 19.

Babarenda Gamage G, Boyle C (2006) Developing the use of environmental impact assessment in commercial organisations: a case study of Formway furniture. Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, 31 May 31–2 June 2006, http://www.mech.kuleuven.be/lce2006/ 072.pdf

Babarenda Gamage G., Boyle C., McLaren S.J., McLaren J. (2008) Life cycle assessment of commercial furniture: A case study of Formway LIFE chair, International Journal of Life Cycle Assessment, 13 (5), pp. 401-411.

Babarenda Gamage, G. and Boyle, C. (2008) Sustainability through Risk assessment: A Case Study of resource risk Proceedings of the 3rd International Conference on Sustainability Engineering and Science, Auckland, NZ, Dec 9-12, 2008.

Ball, D. J., 2002, Environmental Risk Assessment and the Intrusion of Bias, Environment International, 28, pp 529-544

Bare, J.C., Norris, G.A., Pennington, D.W., McKone, T. (2003) TRACI: The tool for the reduction and assessment of chemical and other environmental impacts, Journal of Industrial Ecology, 6 (3-4), pp. 49-78

Barrett, J., Cherrett, N., and Birch, R., 2004. Exploring the application of the ecological footprint to sustainable consumption policy. In K. Hubacek, I. Atsushi and S. Stagl, eds. Proceedings of the international workshop on driving forces of and barriers to sustainable consumption. UK: University of Leeds, 234–247.

Bar-Yam Y. (1997) Dynamics of Complex Systems. Cambridge, MA: Perseus Press

Bastianoni S, Nielsen SN, Marchettini N, Jorgensen SE. (2005) Use of thermodynamic functions for expressing some relevant aspects of sustainability. Int J Energy Res, 29:53–64.

Baumann, H. (1998): Life Cycle Assessment and Decision Making - theories and practises. Göteborg: Chalmers University of Technology AFR Report 183

Baumann, H. and Tillman, A. (2004) The Hitch Hiker's Guide to LCA: An orientation in LCA methodology and application, Studentlitteratur, Lund, ISBN 91-44-02364-2

Bausch, K.C. (2001) The emerging consensus in social systems theory, pp. xxvi+419p. ISBN: 0306465396; 978-030646539-0

BBC (2010) Gulf of Mexico oil leak 'worst US environment disaster' Available at: http://news.bbc.co.uk/2/hi/world/us_and_canada/10194335.stm

Bebbington, J. (2001) 'Sustainable development: a review of the international development, business and accounting literature', Accounting Forum, Vol. 25, No. 2, pp.128–157.

Becker, J. (2004) Making sustainable development evaluations work, Sustainable Development, 12 (4), pp. 200-211.

Begg, David, S. Fischer and R. Dornbusch. 2003. Economics 7th edition. Maidenhead: McGraw-Hill.

Belk, R. (1984) Three Scales to Measure Constructs Related to Materialism: Reliability, Validity and Relationships to Measures of Happiness, Advances in Consumer Research, in T.K. Provo (Ed.) UT: Association for Consumer Research, Vol. 11, p.291.

Bell, S. and S. Morse, (2008) Sustainability Indicators: Measuring the Immeasurable?, Second Edition, London: Earthscan.

Bennet, A. And Bennet, D. (2004) Organisational survival in the new world: The intelligent complex adaptive system, New York: Elsevier

Bennett, E.M., Cumming, G.S., Peterson, G.D. (2005) A systems model approach to determining resilience surrogates for case studies. Ecosystems 8, 945–957.

Berkes, F. and C.S. Seixas (2005) Building Resilience in Lagoon Social-Ecological Systems: A local-level perspective. Ecosystems 8: 967-974.

Berkes, F., Colding, J., Folke, C. (Eds.), (2003) Navigating Social–Ecological Systems: Building Resilience for Complexity and Change, Cambridge University Press, Cambridge, UK.

Berkes, F., J. Colding, and C. Folke, editors (2003) Navigating social–ecological systems: building resilience for complexity and change, Cambridge University Press, Cambridge, UK.

Bertram M (2006) The global and European dimension of aluminium recycling. International Aluminium Institute, European Aluminium Association and Organisation of European Aluminium Refiners and Remelters, http://www.aluminiumcentrum.nl/aluminiumcentrum.nl/files/Doc/Congres%202006/module%20a/2-Mrs._Marlen_Bertram.pdf

Bilec M, Ries R, Matthews HS, Sharrard AL (2006) Example of a hybrid life cycle assessment of construction processes. J Infrastruct Syst 12:207–215

Blinc, R., Zidanšek, A. and Šlaus, I. (2007) 'Sustainable development and global security', Energy, Vol. 32, No. 6, pp.883–890.

Blockley D., Heslop S. (2001) Managing vulnerability and risk for sustainability, Civil Engineering and Environmental Systems, 18 (1), pp. 61-86.

Bonabeau, E., Theraulza, G., Deneubourg, J-L., Aron, S., Camazine, S. (1997) Self-organization in social insects, Santa Fe Institute, Working Paper: Santa Fe, New Mexico

Boothroyd, P (1995). Policy assessment. In Environmental and Social Impact Assessment, F Vanclay and D Bronstein (eds.), pp. 83–126. Chichester: Wiley.

Booysen, F. (2002). An overview and evaluation of composite indices of development. Social Indicators Research, 59, pp. 115–151.

Boscarino, J.A., Adams, R.E., Figley, C.R., Galea, S., Foa, E.B. (2006) Fear of terrorism and preparedness in New York City 2 years after the attacks: Implications for disaster planning and research, Journal of Public Health Management and Practice, 12 (6), pp. 505-513.

Bossel, H. (1999) Indicators for Sustainable Development: Theory, Method, Applications. A Report to the Balaton Group, IISD, Canada.

Bouwman A.F., Van Vuuren D.P., Derwent R.G., Posch M. (2002) A global analysis of acidification and eutrophication of terrestrial ecosystems, Water, Air, and Soil Pollution, 141 (1-4), pp. 349-382.

Boyle C., Coates G.T.K. (2005) Sustainability principles and practice for engineers, IEEE Technology and Society Magazine, 24 (3), pp. 32-39.

Bradbury, H. (2003) Sustaining Inner and Outer Worlds: A Whole-Systems Approach to Developing Sustainable Business Practices in Management, Journal od Management Education, 27 (2), pp. 172-187. DOI 10.1177/1052562903251414, Special Issue: Teaching About the Natural Environment in Management Education

Brand F. (2009) Critical natural capital revisited: Ecological resilience and sustainable development Ecological Economics, 68 (3), pp. 605-612.

Brekke, K.A., 1997. Economic Growth and the Environment: On the Measurement of Income and Welfare. Edward Elgar, Cheltenham.

Brekke, K.A., 1997. Economic Growth and the Environment: On the Measurement of, Income and Welfare. Edward Elgar, Cheltenham.

Bridges J. (2003) Human health and environmental risk assessment: The need for a more harmonised and integrated approach, Chemosphere, 52 (9), pp. 1347-1351.

Brink, P. (1991) Issues of reliability and validity. In: Morse J (ed) Qualitative nursing research: a contemporary dialogue. Sage, London, pp 164–186

Brody, T. A. (1993) The Philosophy Behind Physics, Springer Verlag.

Broman, G., Holmberg, J., Robert, K-H. (2000) Simplicity without reduction: thinking upstream towards the sustainable society, Interfaces, 30:13–25

Brown B.J., Hanson M.E., Liverman D.M., Merideth Jr. R.W. (1987) Global sustainability: Toward definition, Environmental Management, 11 (6), pp. 713-719.

Brown M.T., Herendeen R.A. (1996) Embodied energy analysis and EMERGY analysis: A comparative view, Ecological Economics, 19 (3), pp. 219-235.

Brown, D., J. Dillard and R.S. Marshall. (2006) "Triple Bottom Line: A business metaphor for a social construct." Portland State University, School of Business Administration. Retrieved on: 2007-07-18.

Brown, S.L. and Eisenhardt, K.M. (1997) The Art of Continuous Change: Linking Complexity Theory and Time-Paced Evolution in Relentlessly Shifting Organizations. Administrative Science Quarterly, 42(1):1–35.

Burton, I. and Pushchak, R. (1984) The status and prospect of risk assessment, Geoforum, 15:3

Buselich, K. (2002) An outline of current thinking on sustainability assessment, A background paper prepared for the Western Australia State Sustainability Strategy. Western Australia: Murdoch University.

Cairns Jr. J. (2007) Sustainable co-evolution, International Journal of Sustainable Development and World Ecology, 14 (1), pp. 103-108.

Callens, I. and D. Tyteca (1999). "Towards indicators of sustainable development for firms." Ecological Economics 28(1): 41-53.

Campbell, C. (1998) Consumption and the Rhetorics of Need and Want, Journal of Design History, 11 (3): 235-246

Capra, F. (2004) The hidden connections: A science for sustainable living, Knopf Publishing Group, New York.

Carbon Trust (2010) Carbon footprinting: The next step to reducing your emissions, London: Queen’s Printer and Controller of HMSO.

Carpenter, S., Walker, B., Anderies, J.M., Abel, N. (2001) From Metaphor to Measurement: Resilience of What to What? Ecosystems, 4 (8), pp. 765-781

Carpenter, S.R., Westley, F., Turner, M.G. (2005) Surrogates for resilience of social-ecological systems, Ecosystems, 8 (8), pp. 941-944

Carson, R. (1962) Silent Spring, Harmondsworth: Penguin.

Cerin, P. and Dobers, P. (2001)What does the performance of the Dow Jones Sustainability Index tell us? Eco-Management and Auditing, 8, 123–133

CHAINET (European Network on Chain Analysis for Environmental Decision Support) (1998), Definition document, CML, Leiden University, The Netherlands.

Chaker, A., El-Fadi, K., Chamas, L. and Hatjian, B. (2006) A review of strategic environmental assessment in 12 selected countries. Environmental Impact Assessment Review, 26(1):15-56

Chambers, N. and Lewis, K. (2001) Ecological Footprint analysis: Towards a sustainable indicator for business, ACCA: London.

Chambers, N., Simmons, C. and M. Wackernagel (2000) Sharing nature’s interest: ecological footprint as an indicator of sustainability. London, Earthscan Publications Ltd.

Checkland, P. (1999) Systems Thinking, Systems Practice. Chichester: Wiley.

Chesson, J., Clayton, H., Whitworth, B. (1999) Evaluation of fisheries-management systems with respect to sustainable development, ICES Journal of Marine Science, 56 (6), pp. 980-984.

Choi, T.Y., Dooley K.J., Rungtusanatham M. (2001) Supply networks and complex adaptive systems: Control versus emergence, Journal of Operations Management, 19 (3), pp. 351-366.

Christiansen, K., Heijungs, R., Rydberg, T., Ryding, S.-O., Sund, L., Wijnen, H., Vold, M., (...), Hansen, O.-J. (1995) Applications of Life Cycle Assessments. Summary of report from Expert workshop at Hankø, Norway on LCA, Strategic management, product development and improvement, marketing, and ecolabelling governmental policies

Cilliers, P. (1998) Complexity & Postmodernism. London: Routledge.

Ciroth, A., Becker, H. (2006) Validation - The missing link in life cycle assessment towards pragmatic LCAs, International Journal of Life Cycle Assessment, 11 (5), pp. 295-297.

Clark, W.C., Dickson, N.M. (2003) Sustainability science: the emerging research program. Proceedings of the National Academy of Science 100 (14), 8059–8061.

Cleveland, C., 1992. Energy Quality and Energy Surplus in the Extraction of Fossil Fuels in the U.S. Ecol. Econ., 6: 139-162.

Clift R. (1993) Life cycle assessment and ecolabelling, Journal of Cleaner Production, 1 (3-4), pp. 155-159.

Cobb, C., Halstead, T. And Rowe, J. (1995) The Genuine Progress Indicator: Summary of data and methodology, San Francisco: Redefining Progress.

Cole, H.S.D., Freeman, C., Jahoda, M. and Pavitt, K.L.R. (Eds) (1973) Thinking About the Future: a Critique of the Limits to Growth, Sussex University Press: Chatto and Windus.

Collins A., Flynn A. (2007) Engaging with the ecological footprint as a decision-making tool: Process and responses Local Environment, 12 (3), pp. 295-312.

Cormier, P. O. (1990) California's program for funding commercial and industrial energy projects, Strategic Planning for Energy and the Environment 10 (3), pp. 19-23

Cornelissen, A. (2003) The two faces of sustainability: Fuzzy evaluation of sustainable development, PhD Thesis, Wageningen University, the Netherlands

Costanza R. (1980) Embodied energy and economic valuation, Science, 210 (4475), pp. 1219-1224.

Costanza R. (2000) The dynamics of the ecological footprint concept. Ecol Econ, 32:341–5.

Costanza, R. and Daly, H. (1987) Towards an ecological economics, Ecological Modelling, 38(1-2): 1-7

Costanza, R., Patten, B.C. (1995) Defining and predicting sustainability, Ecological Economics, 15 (3), pp. 193-196.

Covello V.T., Mumpower J. (1985) Risk analysis and risk management: An historical perspective, Risk Analysis, 5 (2), pp. 103-120.

Covello, V. And Wolf, S. (2003) The seven Cardinal rules of risk communication, Water Environment & Technology. Alexandria: 15 (1): 8, 2 pgs

Cowell, S.J., Fairman, R., Lofstedt, R.E. (2002) Use of risk assessment and life cycle assessment in decision making: A common policy research agenda, Risk Analysis, 22 (5), pp. 879-894.

Craig L., Brook J.R., Chiotti Q., Croes B., Gower S., Hedley A., Krewski D., (...), Williams M. (2008) Air pollution and public health: A guidance document for risk managers, Journal of Toxicology and Environmental Health - Part A: Current Issues, 71 (9-10), pp. 588-698.

Craig, P. (2001) 'Energy limits on recycling', Ecological Economics, Vol. 36, No. 3, pp.373–384.

Cravens, D. and Hills, G. (1970) 'Consumerism: a perspective for business', Business Horizons, Vol. 13, No. 4, pp.21–28.

Creazzo J.A., Hammel H.S. (1993) Replacing CFC-11 with HCFC-22 in polyurethane foam, Journal of Cellular Plastics, 29 (2), pp. 146-158.

Crettaz P., Pennington D., Rhomberg L., Brand K., Jolliet O. (2002) Assessing human health response in life cycle assessment using ED10s and DALYs: Part 1 - Cancer effects, Risk Analysis, 22 (5), pp. 931-946.

Cumming, G. S., and J. Collier. 2005. Change and identity in complex systems. Ecology and Society 10(1): 29. [online] URL: http://www.ecologyandsociety.org.ezproxy.auckland.ac.nz/vol10/iss1/art29/

Cumming, G.S., Barnes, G., Perz, S., Schmink, M., Sieving, K.E., Southworth, J., Binford, M., Holt, R.D., Stickler, C., Van Holt, T. (2005) An exploratory framework for the empirical measurement of resilience. Ecosystems 8, 975–987.

Dalal-Clayton, B. and Sadler, B (2002) Strategic Environmental Assessment: A Rapidly Evolving Approach. Available online : http://www.nssd.net/References/KeyDocs/IIED02.pdf

Dalal-Clayton, B. and Sadler, B. (1999) Strategic Environmental Assessment: A rapid Evolving Approach. Available online at: http://www.iied.org/docs/spa/epil8.pdf [February 28, 2006]

Daly HE. (1996) Beyond growth. Boston: Beacon Press.

Daly, H. (1973) Towards a steady state economy. W.H. Freeman, San Francisco.

Daly, H. and Cobb, J. (1990) For the common good, Boston: Beacon Press.

Davidson, K. (2005) 'Towards an integrated sustainability indicator framework', International Journal of Environment, Workplace and Employment, Vol. 1, Nos. 3/4, pp.370–382.

Davis D.L. (1997) Short-term improvements in public health from global-climate policies on fossil-fuel combustion: An interim report, Lancet, 350 (9088), pp. 1341-1349.

de Haan, J. (2006) How emergence arises, Ecological Complexity, 3 (4), pp. 293-301.

Dent, E. And Holt, C. (2001) CAS in war, bureaucratic machine in peace: The U.S. Air Force example, Emergence, 3(3): 90-107

Devuyst, D. (ed). (2001) How Green is the City? Sustainability Assessment and the Management of Urban Environments. New York: Columbia University Press.

Dhalla NK. Yuspeh S. (1976) Forget the Product Life Cycle Concept. Harvard Business Review 54:102-112.

Diamond, J. (2004) Collapse: How Societies Choose to Fail or Succeed, New York: Viking

Didham, R.K. (2006) When are alternative stable states more likely to occur? Oikos 113 (2), 357–362.

Diesendorf, M. Principles of ecological sustainability (1997) Human Ecology, Human Economy: Ideas for an Ecologically Sustainable Future, pp. 64-97 M.Diesendorf and C. Hamilton (eds.), Allen & Unwin, Sydney

Dincer I. (2002) The role of exergy in energy policy making. Energy Policy, 30:137–49.

Dockery D.W., Pope III C.A., Xu X., Spengler J.D., Ware J.H., Fay M.E., Ferris Jr. B.G., Speizer F.E. (1993) An association between air pollution and mortality in six U.S. cities, New England Journal of Medicine, 329 (24), pp. 1753-1759.

DOE (2010) President's Energy Budget Invests in Innovation, Clean Energy, and National Security Priorities, U.S. Department of Energy, Available at: http://www.energy.gov/news/8588.htm

Dooley, K. (1996), "A Nominal Definition of Complex Adaptive Systems," The Chaos Network, 8(1): 2-3.

Dooley, K. (1997) A complex adaptive systems model of organizational change, Non-linear Dynamics, Psychology and the Life Sciences, 1, pp. 69-97.

Dovers, S. (2002). Too deep a SEA? Strategic Environmental Assessment in the era of sustainability. In Marsden, S. and Dovers, S. (Eds) (2002). Strategic Environmental Assessment in Australasia. The Federation Press. Leichhardt, NSW.

Dovers, S. (2005) 'Clarifying the imperative of integration research for sustainable environmental management', Journal of Research Practice, Vol. 1, No. 2, Article M1, http://jrp.icaap.org/content/v.1.2/dovers.html.

Drengson, A. and Y. Inoue, eds. (1995). The Deep Ecology Movement: An Introductory Anthology. Berkeley: North Atlantic Publishers.

Dreyer L.C., Hauschild M.Z., Schierbeck J. (2006) A framework for social life cycle impact assessment, International Journal of Life Cycle Assessment, 11 (2), pp. 88-97

Dreyer, L.C., Niemann, A.L., and Hauschild, M.Z.: Comparison of three different LCIA methods:EDIP97, CML2001 and Eco-indicator 99. Does it matter which one you choose? Int.J.LCA, 8(4), 191-200, 2003

Eawag (2005) Household-Centred Environmental Sanitation: Implementing the Bellagio Principles in Urban Environmental Sanitation, Swiss Federal Institute of Aquatic Science and Technology.

Ecoinvent Centre (2004) Ecoinvent data v1.1. Final reports Ecoinvent 2000 (1–15). Swiss Centre for Life Cycle Inventories, Duebendorf (CD-ROM)

Eggenberger, M. and Partidario, M. (2000) 'Integration: development of a framework to assist the integration of environmental, social and economic issues in spatial planning', Impact Assessment and Project Appraisal, Vol. 18, No. 2, pp.201–207.

Ehrenfeld, (1997) J.R. The Importance of LCAs - Warts and All, Journal of Industrial Ecology, 1 (2), pp. 41-49.

EIA (2005a) Electric Power Annual 2005, Energy Information Administration. Available at: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

EIA (2005b) Country Analysis Brief – China, 2004, International Energy Annual, Energy Information Administration.

Eisenhardt, K.M. and Bhatia, M.M. (2002) Organizational Complexity and Computation. In: Companion to Organizations. J.A.C. Baum (ed.). Oxford: Blackwell, 442–66

Ekins, P. (2000) Sustainability and critical natural capital: conclusions from the CRITINC project, Available at: http://www.keele.ac.uk/depts/spire/Working_Papers/CRITINC/WP14.pdf

Ekins, P. and Simon, S. (2003) An illustrative application of the CRITINC framework to the UK, Ecological Economics, 44(2-3): 255-275

Ekins, P., Simon, S., Deutsch, L., Folke, C. and De Groot, R. (2003) A framework for the practical application of the concept of critical natural capital and strong sustainability, Ecological Economics, 44(2-3): 165-185

Ekvall, T., and Finnveden, G. (2001) Allocation in ISO 14041 - a critical review, Journal of Cleaner Production, 9 (3), pp. 197-208

Ekvall, T., Weidema, B.P. (2004) System boundaries and input data in consequential life cycle inventory analysis, International Journal of Life Cycle Assessment, 9 (3), pp. 161-171.

Elkington, J. (1999). Triple bottom-line reporting: Looking for balance. Australian CPA, (March), 19–21.

Elkington, J. (2004). Enter the triple bottom line. In A. Henriques & J. Richardson (Eds) The triple bottom line, does it all add up? Assessing the sustainability of business and CSR (pp. 1-16). London: Earthscan Publications Ltd.

Eoyang, G., (1997) Coping with Chaos: Seven Simple Tools. Cheyenne, WY: Lagamo Corporation.

ESAA (2005) Electricity Gas Australia, Energy Supply Association of Australia, Melbourne.

EUROPEN (2001) Position Paper: Recent policy developments in Denmark and Germany seriously threaten packaging chain goal of continuous environmental improvement, Brussels

Fava J.A. (1998) Life cycle perspectives to achieve business benefits: From concept to technique, Human and Ecological Risk Assessment (HERA), 4 (4), pp. 1003-1017.

Fenner, R., Ainger, C., Cruickshank, H., Guthrie, P. (2006) Widening engineering horizons: addressing the complexity of sustainable development. Engineering Sustainability, 159 (ES4), 145-154.

Ferguson, N.M., Keeling, M.J., Edmunds, W.J., Gani, R., Grenfell, B.T., Anderson, R.M., Leach, S. (2003) Planning for smallpox outbreaks, Nature, 425 (6959), pp. 681-685.

Fet A, Skaar C (2006) Eco-labeling, product category rules and certification procedures based on ISO 14025 requirements. Int J LCA 11(1):49–54

Fiebleman, J. (1954) Theory of integrative levels. The British Journal for the Philosophy of Science, 5(17), 59–66.

Fiksel J. (2003) Designing resilient, sustainable systems. Environment Science and Technology 37(23): 5330–5339.

Fiksel J. (2006) Sustainability and resilience: toward a systems approach. Sustainability: Science, Practice, and Policy 2(2): 14–21.

Finnveden G. (2000) On the limitations of life cycle assessment and environmental systems analysis tools in general, International Journal of Life Cycle Assessment, 5 (4), pp. 229-238.

Finnveden G., Moberg A. (2005) Environmental systems analysis tools - An overview , Journal of Cleaner Production, 13 (12), pp. 1165-1173.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R. d, Hellweg, S., Koehler, A., Pennington, D., Suh, S.g (2009) Recent developments in Life Cycle Assessment, Journal of environmental management, 91 (1): 1 -21

Finucane M.L., Slovic P., Mertz C.K., Flynn J., Satterfield T.A. (2000) Gender, race, and perceived risk: The 'white male' effect, Health, Risk and Society, 2 (2), pp. 170-172.

Fischhoff B. (1995). Risk perception and communication unplugged. Risk Analysis. 15: 137-145.

Flemström, K., Carlson, R., & Erixon, M. (2004). Relationships between Life Cycle Assessment and Risk Assessment—Potentials and Obstacles. Naturvardsverket, 071-SNV Rapport 5379. Stockholm, Sweden: Swedish Environmental Protection Agency.

Flynn J., Slovic P., Mertz C.K. (1994) Gender, race, and perception of environmental health risks, Risk Analysis, 14 (6), pp. 1101-1108.

Folke, C. (2006) Resilience: The emergence of a perspective for social-ecological systems analyses. Global Environmental Change 16, 253–267.Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S.,Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., Falkenmark, M.,Gordon, L.,Kaspersson, R.,Kautsky,N., Kinzig, A., Levin, S.A.,M¨aler, K.-G., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid,W., Rockstr¨om, J., Savenije, H. and Svedin, U. (2002) Resilience and SustainableDevelopment: BuildingAdaptive Capacity in a World of Transformations. Background Paper forWSSD. Paris: International Council for Science. On WWW at http://www.sou.gov.se/mvb/pdf/resiliens.pdf. (Accessed 12/9/07).

Folke, C., Carpenter, S.R., Walker, B.H., Scheffer, M., Elmqvist, T., Gunderson, L.H., Holling, C.S. (2004) Regime shifts, resilience and biodiversity in ecosystem management. Annual Review in Ecology, Evolution and Systematics 35, 557–581.

Folke, C.; Carpenter, S.; Elmqvist, T.; Gunderson, L.; Holling, C.S.; Walker, B. Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio 2003, 31, 5, 437-440.

Formway (2004) LIFE-You are liberated, Formway Furniture Ltd, http://www.formway.com/library/images/Life_Brochure_FW02_0704.pdf

Forrester, J.W. (1971) World Dynamics, 2nd edn., Portland, Oregon: Productivity Press

Frankl, P., Rubik, F. (2000) Life Cycle Assessment in Industry and Business. Adoptions, Patterns, Applications and Implications, Springer Verlag, Heidelberg

Fricker, A. (1998). Measuring up to Sustainability. Futures. Vol 30. No.4 pp367-375.

Frischknecht R, Jungbluth N, Althaus H, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2005) The ecoinvent database: overview and methodological framework. Int J LCA 10(1):3–9

Fukushima, Y. and M. Hirao (2002) A structured framework and language for scenario-based life cycle assessment. International Journal of Life Cycle Assessment 7(6): 317–329.

Fuller, K. (2002) Impact Assessment for a sustainable development report: IAIA output report (WS07) proceedings of the 22nd annual conference of the International Association for Impact Assessment

Funk J. (2008) Systems, components and technological discontinuities: The case of the semiconductor industry, Industry and Innovation, 15 (4), pp. 411-433.

Galbraith, J. (1984) The affluent society, New American Library

Gale R.P. and Cordray S.M. (1994) Making sense of sustainability: nine answers to "What should be sustained?', Rural Sociology, 59 (2), pp. 311-332.

Gallopin, G.C. (2006) Linkages between vulnerability, resilience, and adaptive capacity, Global Environmental Change 16, 293–303.

Gamage G.B., Boyle C. (2008) Sustainable development: A review of progress, stagnation and potential, International Journal of Sustainable Development, 11 (1), pp. 45-60.

Gamage G.B., Boyle C. (2008b) Sustainable development: A review of progress, stagnation and potential, International Journal of Sustainable Development, 11 (1), pp. 45-60.

Gardner DM. (1987) The Product Life Cycle: A Critical Look at the Literature. In Review of Marketing Houston, M. (ed.) Chicago: American Marketing Association.

Gardner R. (2003) Overview and characteristics of some occupational exposures and health risks on offshore oil and gas installations, Annals of Occupational Hygiene, 47 (3), pp. 201-210.

Garmestani, A. S., C. R. Allen, and L. Gunderson. 2009. Panarchy: discontinuities reveal similarities in the dynamic system structure of ecological and social systems. Ecology and Society 14(1): 15. [online] URL: http://www.ecologyandsociety.org/vol14/iss1/art15/

Gasparatos, A., El-Haram, M., & Horner, M. (2007). A critical review of reductionist approaches for assessing the progress towards sustainability. Environmental Impact Assessment Review. doi: 10.1016/j.eiar.2007.09.002.

Geels, F.W. (2005) Technological Transitions and System Innovations: a Co-evolutionary and Socio-technical Analysis. Cheltenham: Edward Elgar.

Gell-Mann, M. (1994) The Quark and the Jaguar. New York: Freeman & Co.

George, C. (1999). Testing for sustainable development through environmental assessment, Environmental Impact Assessment Review, 19:175-200

George, C. (2001), "Sustainability appraisal for sustainable development: integrating everything from jobs to climate change", Impact Assessment and Project Appraisal, 19, pages 95–106.

Ghersa C.M., Roush M.L., Radosevich S.R., Cordray S.M. (1994) Coevolution of agroecosystems and weed management - Weed-management practices have become closely linked to social and economic, rather than biological, factors, BioScience, 44 (2), pp. 85-94.

Giannetti BF, Barrella FA, Almeida CMVB. (2006) A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting. J Clean Prod 14:201–10.

Gibson, R. (2001), Specification of Sustainability-based Environmental Assessment Decision Criteria and Implications for Determining 'Significance' in Environmental Assessment, available at http://www.sustreport.org/downloads/SustainabilityEA.doc., last accessed 02/05/2009.

Gibson, R., Agnolin, J., Hassan, S., Lawrence, D., Robinson, J., Tansey, J., Watson, J., Whitelaw, G., (2001) Specifications of sustainability-based environmental assessment decision criterion and implications for determining "significance" in environmental assessment.

Gibson, R, S. Hassan, S. Holtz, J. Tansey & G. Whitelaw (2005) Sustainability Assessment Criteria, Processes and Applications, Earthscan Publications Ltd, London

Gibson, R.B. (2006) 'Sustainability assessment: basic components of a practical approach', Impact Assessment and Project Appraisal, Beech Tree Publishing, September, Vol. 24, No. 3, pp.170–182.

Gleick, J. (1987) Chaos: Making a new science, New York: penguin Books

Glesne, C., & Peshkin, A. (1992). Becoming qualitative researchers. New York: Longman.

Global Footprint Network, (2009) Ecological Footprint Standards 2009. Oakland: Global Footprint Network. Available at www.footprintstandards.org.

Global Reporting Initiative (2006). G3 Online Boston USA: Global Reporting Initiative http://www.globalreporting.org.

Gluch, P., Baumann, H., (2004) The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Building and Environment 39, 571–580.

Godfrey-Smith, P. (2003) Theory and Reality: An introduction to the philosophy of science, University of Chicago Press

Goedkoop M, Effting S, Coltignon M (2000): The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment. Manual for Designers. Second edition 17-4-2000. PR4 Consultants B.V., Amersfoort, The Netherlands

Goedkoop, M. and Spriensma, R. (2001) The Eco-Indicator 99: A damage oriented method for Life cycle impact assessment- Methodology Report, 3rd Edition, Pré Consultants , B.V. Amersfoort, Netherlands

Goldstein, J. (1999) "Emergence as a construct: History and issues". Emergence: A Journal of Complexity Issues in Organizations and Management, 1 (1), 49-72.

Gotts N.M. Resilience, panarchy, and world-systems analysis (2007) Ecology and society, 12 (1), art. no. 24

Government of Western Australia (2003), Hope for the Future: the Western Australian State Sustainability Strategy (Department of the Premier and Cabinet, Perth, Western Australia)

Graedel T.E., Klee R.J. (2002) Getting serious about sustainability, Environmental Science and Technology, 36 (4), pp. 523-529.

Gray, P. C. R. and Wiedemann, P. M. (1999) Risk management and sustainable development: mutual lessons from approaches to the use of indicators, Journal of Risk Research, 2: 3, 201 — 218

Grier, B. (1980) One Thousand Years of Mathematical Ps.vchologv (Paper presented at Society for Mathematical Psychology Convention, Madison, Wisconsin

Grimm, V. (1999) Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future? Ecological Modelling 115, 129–148.

Guba, E. and Lincoln, Y. (1989) Fourth Generation Evaluation, Sage, California.

Guijt, I. and Moiseev, A. (2001) Resourcekit for sustainability assessemtn: Part A, Gland, IUCN, Switzerland

Guin´ee J and Heijungs R. (1993) A proposal for the classification of toxic substances within the framework of life-cycle assessment of products, Chemosphere, 26(10):1925–44

Guinée JB (final editor); Gorée M, Heijungs R, Huppes G, Kleijn R, Koning A de, Oers L van, Wegener Sleeswijk A, Suh S, Udo de Haes HA, Bruijn H de, Duin R van, Huijbregts MAJ (2002) Handbook on life cycle assessment–operational guide to the ISO Standards. ISBN 1-4020-0228-9. Kluwer Academic, Dordrecht

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Sleeswijk, A., Suh, S., Udo de Haes, H., de Brujin, H., van Duin, R., Huijbregts, M., (2001) Life Cycle Assessment: An operational guide to the ISO standards, Ministry of Housing , Spacial Planning and the Environment and Centre of Environmental Science (CML), Leiden

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, J.A., van Duin, R. and Huijbregts, M.A.J. (2002) Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in Industry and Science, Kluwer Academic Publishers, Dordrecht.

Gunderson, L. (1994) Fire patterns in the southern everglades. In: S. M. Davis, & J. C.Ogden (Eds.), Everglades. The ecosystem and its restoration (pp. 291–305). Delray Beach, FL: St. Lucie Press.

Gunderson, L., Allen, C and Holling, C. (2009) Foundations of Ecological Resilience, Island Press page 177

Gunderson, L.H. and Holling, C.S. (eds) (2002) Panarchy: Understanding Transformation in Human and Natural Ecosystems. Washington, DC: Island.

Gwehenberger, G. & Narodoslawsky, M. (2007) The Sustainable Process Index SPI as an engineer's tool for environmental impact assessment of processes: the sugar industry as a case study, WIT Transactions on Ecology and the Environment, pg:333 -340

Hacking T., Guthrie P. (2006) Sustainable development objectives in impact assessment: Why are they needed and where do they come from? Journal of Environmental Assessment Policy and Management, 8 (3), pp. 341-371.

Hacking T., Guthrie P. (2008) A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment, Environmental Impact Assessment Review, 28 (2-3), pp. 73-89.

Hammersley, M. (1992) What's Wrong with Ethnography? Routledge, London

Hammond GP. (2004) Engineering sustainability: thermodynamics, energy systems and the environment. Int J Energy Res, 28:613–39.

Hammond, D. (2003) The Science of Synthesis: Exploring the Social Implications of General Systems Theory. Boulder: University Press of Colorado.

Hammond, GP. (2003) Book Review: Kline SJ. The Low-Down on Entropy and Interpretive Thermodynamics, Proceedings of the Institution of Mechanical Engineers Part A: Journal of Power and Energy 217(3):337–339.

Harder, J., Robertson, P. And Woodward, H. (2004) The spirit of the new3 workplace: Breathing life into organisations, Organization Development Journal, 22(2):79-103

Harding, Stephan. (1997) What is Deep Ecology? Retrieved on January 3, 2010 from http://www.livingspark.net/pdf/WHAT%20IS%20DEEP%20ECOLOGY.pdf

Harris P.R., Smith V. (2005) When the risks are low: The impact of absolute and comparative information on disturbance and understanding in US and UK samples, Psychology and Health, 20 (3), pp. 319-330.

Hartwick JM. (1992) Deforestation and national accounting. Environ Resour Econ, 2:513–21.

Hatch, M., & Yanow, D. (2003). Organization theory as an interpretive science. In H. Tsoukas & C. Knudsen (Eds.), The Oxford handbook of organization theory (pp. 63-87). Oxford, UK: Oxford University Press.

Hauschild, M. and Potting, J.: Spatial differentiation in life cycle impact assessment – the EDIP2003 methodology. Guidelines from the Danish Environmental Protection Agency, Copenhagen, 2004 (in press).

Heijungs R, Huppes G, Guine´e J. A scientific framework for LCA. Deliverable (D15) of CALCAS Project. Institute of Environmental Sciences, Leiden University, (CML), http://www.calcasproject.net; 2009.

Heijungs, R., Guinée, J.B. (2007) Allocation and 'what-if' scenarios in life cycle assessment of waste management systems, Waste Management, 27 (8), pp. 997-1005.

Heijungs, R., Huppes, G. Guinée, J. (2009) A scientific framework for LCA. Deliverable D15 of the CALCAS project. ENEA, [online] URL: http://www.estis.net/includes/file.asp?site=calcas&file=8417BD07-5CCC-48F1-8243-91B42A40D9CB

Heijungs, R., Huppes, G. Guinée, J. A scientific framework for LCA. Deliverable D15 of the CALCAS project. ENEA, 2009. http://fr1.estis.net/includes/file.asp?site=calcas&file=631CC8B9-1C62-49FC-A2FD-AE82940D0C82.

Hendrickson, C. T., Lave, L. B., Matthews, H. S. (2006). Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Resources for the Future Press.

HERA (2002) HERA Guidance Document Methodology – February 2005. Available at: http://www.heraproject.com/files/HERA%20TGD%20February%202005.pdf

Hermans F., Knippenberg L. (2006) A principle-based approach for the evaluation of sustainable development, Journal of Environmental Assessment Policy and Management, 8 (3), pp. 299-319.

Heycox, J. (1999). Integrating data for sustainable development: introducing the distribution of resources framework. Novartis Foundation Symposium 220: Environmental statistics - analysing data for environmental policy, London, John Wiley & Sons.

Hirsch, F. (1976) SocialLlimits to Growth. Cambridge: Harvard University Press.

Hoekstra, A.Y. and Hung, P.Q., (2002) Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No.11, IHE, the Netherlands.

Hoekstra. A., Chapagain, A., Aldaya, M. and Mekonnen, M. (2009) Water Footprint Manual: State of the Art 2009, Water Footprint Network, Enschede, The Netherlands Available at: http://www.waterfootprint.org/downloads/WaterFootprintManual2009.pdf Retrieved April, 2010

Holland, J. H. (1975) Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, andArtificial Intelligence, USA: MIT Press, 1975.

Holland, J. H. (1992) Complex adaptive systems Daedalus, vol. 121, pp. 17-30, Winter, 1992.

Holland, J. H. (1995) Hidden Order: How Adaptation Builds Complexity; Helix Books: Reading, MA,.

Holland, J. H. (2003) Can the principle of the ecological footprint be applied to measure the environmental sustainability of business? Corporate Social - Responsibility and Environmental Management, 10 (4):224 -232

Holling, C. S. (1973) Resilience and stability of ecological systems, Annual Review of Ecology and Systematics, 4, pp. 1-23

Holling, C. S. (1986) The resilience of terrestrial ecosystems: local surprise and global change. In C. C. William, & R. E. Munn (Eds.), Sustainable development of the biosphere (pp. 292–320). New York: Cambridge University Press for the International Institute for Applied Systems Analysis.

Holling, C. S. (1996) Engineering resilience versus ecological resilience. In: Schulze, P. Ed. Engineering within Ecological Constrains, Washington, D. C.: National Academy.

Holling, C. S. (2001) Understanding the complexity of economic, ecological, and social systems. Ecosystems, 4 (5), 390-405.

Holling, C. S. (2004) From complex regions to complex worlds. Ecology and Society 9(1): 11. [online] URL: http://www.ecologyandsociety.org/vol9/iss1/art11/

Holling, C. S. and L. H. Gunderson (2002) Resilience and adaptive cycles. Pages 25-62 in L. H. Gunderson and C. S. Holling, editors. Panarchy: understanding transformations in human and natural systems. Island Press, Washington, D.C., USA.

Holling, C., Carpenter, S., Brock, W. And Gunderson, L (2002b) Discoveries for sustainable futures, in Panarchy: Understanding Transformation in Human and Natural Ecosystems. Washington, DC: Island, pp396.

Holling, C.S., L.H. Gunderson, D. Ludwig. (2002a) In quest of a theory of adaptive change. In L.H Gunderson, and C.S Holling, editors. Panarchy: Understanding Transformations in Systems of Humans and Nature. Washington, D.C., USA: Island Press.

Hollnagel, E., Woods, D. D., and Leveson, N. eds. (2006) Resilience engineering—Concepts and precepts, Ashgate, Aldershot, U.K.

Holmberg J., Lundqvist U., Robert K.-H., Wackernagel M. (1999) The ecological footprint from a systems perspective of sustainability, International Journal of Sustainable Development and World Ecology, 6 (1), pp. 17-33.

Holmberg, J., Robèrt, K.-H., Eriksson, K.-E. Socio-ecological principles for sustainability (1996) Getting Down to Earth - Practical Applications of Ecological Economics. Cited 32 times. R. Costanza, S. Olman and J. Martinez-Alier (eds.), Island Press, Washington D

Huang, L., Duan, B., Bi, J., Yuan, Z. and Ban, J. (2010) 'Analysis of Determining Factors of the Public's Risk Acceptance Level in China', Human and Ecological Risk Assessment: An International Journal, 16: 2, 365 — 379

Hubler A.W. (2005) Predicting complex systems with a holistic approach, Complexity, 10 (3), pp. 11-16.

Hürlimann, M. (2009) Dealing with Real-World Complexity: Limits, Enhancements and New Approaches for Policy Makers, Gabler, Wiesbaden

Hueting, R., and Reijndres, L. (2004). Broad sustainability contra sustainability: the proper construction of sustainability indicators. Eco-efficiency as abandonment of the nature. Ecological Economics(38), 311-315.

Huijbregts M.A.J., Thissen U., Guinee J.B., Jager T., Kalf D., Van De Meent D., Ragas A.M.J., (...), Reijnders L. (2000a) Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA, Chemosphere, 41 (4), pp. 541-573.

Huijbregts M.A.J., Thissen U., Guinee J.B., Jager T., Kalf D., Van De Meent D., Ragas A.M.J., (...), Reijnders L. Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA (2000) Chemosphere, 41 (4), pp. 541-573.

Huijbregts M.A.J., Thissen U., Jager T., Van De Meent D., Ragas A.M.J. (2000b) Priority assessment of toxic substances in life cycle assessment. Part II: Assessing parameter uncertainty and human variability in the calculation of toxicity potentials, Chemosphere, 41 (4), pp. 575-588.

Hunkeler D. (2006) Societal LCA methodology and case study. International Journal of Life Cycle Assessment, 11 (6), pp. 371-382.

Hunkeler D; Rebitzer G (2002): Life Cycle Costing – Paving the Road to Sustainable Development? Editorial in: Gate to EHS: Life Cycle Management, March 25th, 2002. Ecomed publishers

Hunt, R.G. and Franklin W.E. (1996) LCA: How it came about: Personal reflections on the origin and development of LCA in the USA. International Journal of Life Cycle Assessment 1(1): 4-7

Hunter, J. E. and Schmidt, F. L. (1990) Methods of meta-analysis: Correcting error and bias in research findings. Newsbury Park: Sage Publications.

Hussey, D.M., Kirsop, P.L., Meissen, R.E. (2001) Global reporting initiative guidelines: an evaluation of sustainable development metrics for industry, Environmental Quality Management.

IIDEX/NeoCon (2011) International Interior Design Exposition. Available from: http://www.iidexneocon.com/2011/expo/attendee/about-iidex-neocon (accessed 04/10/09).

IISD, (1997) Assessing Sustainable Development: Principles in Practice, Hardi, P. And Zdan, T., International Institute for Sustainable Development, Winnipeg

International Standardization Organization (ISO) (2006). Environmental management – life cycle assessment – principles and framework; 2006. ISO 14040.

IPCC (2001) IPCC Third Assessment Report: Climate change 2001, Intergovernmental Panel on Climate Change. Available from: http://www.ipcc.ch/pub/online.htm (accessed 04/01/09).

ISO (International Organization for Standardization), 2006. ISO 14040:2006(E) Environmental Management – Life Cycle Assessment – Principles and Framework.ISO, 2006).

ISO 14025:2006 Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures

ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework

ISO 31000:2009 Risk management -- Principles and guidelines

ISO, (2006a) ISO, ISO 14040 International Standard, Environmental Management – Life Cycle Assessment – Principles and Framework, International Organisation for Standardization, Geneva, Switzerland (2006).

ISO, (2006b) ISO, ISO 14044 International Standard, Environmental Management – Life Cycle Assessment – Requirements and Guidelines, International Organisation for Standardisation, Geneva, Switzerland (2006).

ISO, 1997 ISO (International Organization for Standardization), 1997. ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO/IEC 31010:2009 Risk management -- Risk assessment techniques

Jackson, T. (2000) 'The unfinished symphony: an evolutionary perspective on the conception of sustainable development', International Journal of Sustainable Development, Vol. 3, No. 3, pp.199–220.

Jackson, T., Jager, W. and Stagl, S. (2004) Beyond insatiability: Needs theory, consumption and sustainability, Working Paper Series Number 2004/2, Sustainable Technologies Programme, Centre for Environmental Strategy, University of Surrey, Guildford

Janssen, M. A., Ö. Bodin, J. M. Anderies, T. Elmqvist, H. Ernstson, R. R. J. McAllister, P. Olsson, and P. Ryan. 2006. Toward a network perspective of the study of resilience in social-ecological systems. Ecology and Society 11(1):15. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art15/.

Jantsch, E. (1980). The Self-Organizing Universe. Oxford: Pergaman Press.

Jenkins B, Annandale D, Morrison-Saunders A. (2003) Evolution of a sustainability assessment strategy for Western Australia. Environ Plan Law J, 201(1):56– 65.

Jevons, W. (1874) The Principles of Science: A Treatise on Logic and Scientific Method, Dover Publications, Reprinted with a foreword by Ernst Nagel, New York, NY, 1958.

Jolliet O, Rosenbaum R, Chapman PM, McKone T, Margni M, Scheringer M, Straalen N, Wania F (2006) Establishing a framework for life cycle toxicity assessment. Findings of the Lausanne Review Workshop. Int J Life Cycle Assess 11:209–212

Kauffman, S (1993) The Origins of Order: Self-Organization and Selection in Evolution, New York, USA: Oxford University Press

Kauffman, S., (1995) At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Oxford University Press, New York, p. 321.

Kauffman, S.A. (1980) Systems One: Introduction to Systems Thinking, SA Carlton: Minneapolis, MN

Kaufman, I. and Channon, D. (1973) 'International consumerism: a threat or opportunity?', Industrial Marketing Management, Vol. 3, No. 1, pp.1–14.

Kaufmann, R. And Cleveland, C. (1995) Measuring sustainability: needed – an interdisciplinary approach to an interdisciplinary concept, Ecological Economics, 1:109-112.

Kelly, K. (1994) Out of control: The new biology of machines, social systems, and the economic world, Reading, MA: Addison-Wesley Publishing Company

Kelso, J.A.S. (Ed.) (2005) Understanding Complex Systems; Springer-Verlag: Heidelberg

Kemp, R. (1994) Technology and the transition to environmental sustainability. The problem of technological regime shifts, Futures, 26 (10), pp. 1023-1046.

Kettle, D. A. (2004). A Sustainability Action Planning Tool. International Conference on Sustainability Engineering and Science, 6-9 July 2004, Auckland, NZ.

Kettle, D. A. (2006). 'An Urban 3-Waters Infrastructure Sustainability Decision-Making Process'. A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Architecture and Planning, October 2006. School of Architecture and Planning, National Institute of Creative Arts and Industries, The University of Auckland, Auckland, New Zealand.

Kikuchi, Y., Hirao, M. (2009) Hierarchical activity model for risk-based decision making: Integrating life cycle and plant-specific risk assessments, Journal of Industrial Ecology, 13 (6), pp. 945-964

Kimberlin, C.L. and Winterstein, A.G. (2008) Validity and reliability of measurement instruments used in research, American Journal of Health-System Pharmacy, 65 (23), pp. 2276-2284.

King-Irani, L. (2007) 'Iraq: A look back', Orbis, Vol. 5, No. 1, pp.91–106.

Kinzig AP, Pacala SW and Tilman D. editors. 2002. The Functional Consequences of Biodiversity. Princeton University Press, Princeton, N.J.

Kirk, J., and Miller, M. L. (1986). Reliability and validity in qualitative research. Beverly Hills: Sage Publications.

Kirkeleit J., Riise T., Bratveit M., Moen B.E. (2008) Increased risk of acute myelogenous leukemia and multiple myeloma in a historical cohort of upstream petroleum workers exposed to crude oil, Cancer Causes and Control, 19 (1), pp. 13-23.

Klare, M.T. (2001)The new geography of conflict, Foreign Affairs, 80 (3), p. 49.

Klepper S. (1996) Entry, Exit, Growth, and Innovation over the Product Life Cycle, American Economic Review, 86 (3), pp. 562-583.

Klepper S. (1997) Industry life cycles, Industrial and Corporate Change, 6 (1), pp. 145-181.

Kloepffer W. Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95) (2008) International Journal of Life Cycle Assessment, 13 (2), pp. 89-94.

Klopffer W. (2003) Life-cycle based methods for sustainable product development, International Journal of Life Cycle Assessment, 8 (3), pp. 157-159.

Klöpffer, W. (1996) Allocation Rule for Open-Loop Recycling in Life Cycle Assessment - A Review, International Journal of Life Cycle Assessment, 1 (1), pp. 27-31.

Koff, H. and Duprez, D. (2009) The 2005 riots in France: The international impact of domestic violence, Journal of Ethnic and Migration Studies, 35 (5), pp. 713-730.

Kosko, B. (1992) Neural networks and fuzzy systems, Prentice-Hall International Inc., New Jersey

Kotas TJ. (1985) The exergy method of thermal plant analysis. London: Butterworths

Kouloumpis V.D., Kouikoglou V.S., Phillis Y.A. (2008) Sustainability assessment of nations and related decision making using fuzzy logic, IEEE Systems Journal, 2 (2), pp. 224-236.

Krotscheck C., Narodoslawsky M. (1996) The Sustainable Process Index. A new dimension in ecological evaluation, Ecological Engineering, 6 (4), pp. 241-258.

Krotscheck, C., Narodoslawsky, M. (1996) The Sustainable Process Index. A new dimension in ecological evaluation, Ecological Engineering, 6 (4), pp. 241-258.

Krysiak, F. C. and D. Krysiak: 2006, 'Sustainability with Uncertain Future Preferences', Environmental and Resource Economics 33, 511–531.

Kunstler, J. (2005) The long emergency: Surviving the converging catastrophes of the twenty-first century, New York: Atlantic Monthly Press.

Kurtz, C.F. and Snowden, D.J. (2003) ‘‘The new dynamics of strategy: sense-making in a complex and complicated world’’, IBM Systems Journal, Vol. 42 No. 3, pp. 462-83.

Langton, C. G. (1990) "Computation at the edge of chaos: phase transitions and emergent computation," Proceedings of the ninth annual international conference of the Center for Nonlinear Studies on Selforganizing,Collective, and Cooperative Phenomena in Natural and Artificial Computing Networks on Emergent computation, 1990 , pp. 12-37

Larsen HF, Hauschild MZ (2007) Evaluation of ecotoxicity effect indicators for use in LCIA. Int J Life Cycle Assess 12:24–33

Lawn, P.A. "A theoretical foundation to support the Index of Sustainable Economic Welfare (ISEW), Genuine Progress Indicator (GPI), and other related indexes". Ecological Economics 44 (2003) 105-118.

Lee N. Integrated approaches to Impact Assessment: substance or make-believe? Environmental Assessment Yearbook. Institute of Environmental Management and Assessment/EIA Centre. Lincoln/ Manchester: University of Manchester; 2002. p. 14–20.

Lélé, S. M. (1991) Sustainable Development: A Critical Review. World Development, 19(6), 607-621.

Leontief, W. (1936) Quantitative input-output relations in the economic system of the United States, Review of Economics and Statistics, 18 (3), pp. 105-125.

Levin, S. A. (1992) The problem of pattern and scale in ecology, Ecology, 73: 1943-1967

Levin, S. A. (1998) Ecosystems and the Biosphere as Complex Adaptive Systems Ecosystems, Biomedical and Life Sciences and Earth and Environmental Science, vol. 1, pp. 431-436, Sep, 1998.

Levin, S. A. (1999) Fragile dominion: Complexity and the commons, Perseus Books, Reading, MA

Lewin, R. (1992). Complexity: Life at the Edge of Chaos. New York: MacMillan.

Lewis L, Gertsakis J, Grant T, Morelli N, Sweatman A (2001) Design + environment: A global guide to designing greener goods. Greenleaf Publishing, Sheffield, UK

Lichtenstein, B. (2000) Emergence as a process of self-organising: New assumptions and insights from the study on non-linear dynamic systems, Journal of Organisational Change Management, 13(6):526-544

Lichtenstein, B. (2007) A matrix of complexity for leadership, Complex systems leadership theory, pp. 285-304. Hazy J., Goldstein J., and Lichtenstein B. (Eds), Boston, MA: ISCE Press.

Lincoln, Y. S., and Guba, E. G. (1985) Naturalistic inquiry. Beverly Hills, CA: Sage.

Lintott, J. (1998) ‘Beyond the economics of more: the place of consumption in ecological economics’, Ecological Economics, Vol. 25, No. 3, pp.239–248.

Liou, M., Yeh, S. and Yu, Y. (2006) Reconstruction and systemization of the methodologies for strategic environmental assessment in Taiwan, Environmental Impact Assessment Review, 26(2): 170-184

Liu K.F.R. (2007) Evaluating environmental sustainability: An integration of multiple-criteria decision-making and fuzzy logic, Environmental Management, 39 (5), pp. 721-736.

Liu, K.F.-R. and Yu, C.-W (2009) Integrating case-based and fuzzy reasoning to qualitatively predict risk in an environmental impact assessment review, Environmental Modelling and Software 24 (10), pp. 1241-1251

Lobiondo-Wood, G. and Haber, J. (1990) Nursing Research: Methods, Critical Appraisal and Utilisation, 2nd edn. Mosby, St Louis

Lockie, S., & Jennings, S. (2003). The social impacts of natural resource use and condition: The invisible dimension of coastal resource management. In B. Pritchard, A. Curtis, J. Spriggs & R. Le Heron (Eds) Social dimensions of the triple bottom line in rural Australia (pp. 131-143). Canberra: Bureau of Rural Sciences.

Loh J, Green R.E, Ricketts T, Lamoreux J, Jenkins M, Kapos V, Randers J. (2005) The Living Planet Index: using species population time series to track trends in biodiversity. Phil. Trans. R. Soc. B. 360:289–295

Long, T. and Johnson, M. (2000) Rigour, reliability and validity in qualitative research, Clinical Effectiveness in Nursing, 4 (1), pp. 30-37.

Lorenz, E. N. (1963) 'Deterministic non-periodic flow', Journal of the Atmospheric Sciences 20, 130–141.

Lundin, U., 2003. Indicators for Measuring the Sustainability of Urban Water Systems—a Life Cycle Approach, PhD Thesis, Department of Environmental Systems Analysis, Chalmers University of Technology, Go¨ teborg, Sweden.

Marin A.W., Tobler M. (2003) The purpose of LCA in environmental labels and concepts of products: 18th discussion forum on life cycle assessment Zürich, International Journal of Life Cycle Assessment, 8 (2), pp. 115-116.

Markose S.M. (2005) Computability and evolutionary complexity: Markets as complex adaptive systems (CAS), Economic Journal, 115 (504)

Marsden, S. and Dovers, S. (2002). Conclusions: Prospects for SEA. In Marsden, S. and Dovers, S. (Eds) (2002). Strategic Environmental Assessment in Australasia. The Federation Press. Leichhardt, NSW.

Martin, A., Blowers, A. and Boersema, J., (2006) 'Is environmental scarcity a cause of civil wars?', Environmental Sciences, Vol. 3, No. 1, pp.1–4

Martin, S. (2002) "Sustainability, Systems Thinking and Professional Practice". Planet, 4: 20-21

Martinez-Alier, J., Munda, G., & O'Neill, J. (1998). Weak comparability of values as a foundation for ecological economics. Ecological Economics, 26, 277–286. doi:10.1016/S0921-8009(97)00120-1.

Maslow A. (1968) Toward a psychology of being,3. ed., New York: D. Van Nostrand Company

Maslow, A. 1954. Motivation and Personality, Harper and Row, New York

Matthews, H.S., L. Lave and H. MacLean (2002) 'Life Cycle Impact Assessment: A Challenge for Risk Analysts', Risk Analysis 22: 853-60.

Maturana, H. and F. Varela (1992). The Tree of Knowledge. Boston: Shambhala.

Max-Neef. M.A. (1992) 'Development and human needs', in Ekins, P. and Max-Neef, M.A. (Editors) Real –1ife Economics: understanding wealth creation, Routledge, London, New York.

McCarthy I.P., Tsinopoulos C., Allen P., Rose-Anderssen C. (2006) New product development as a complex adaptive system of decisions, Journal of Product Innovation Management, 23 (5), pp. 437-456.

McClellan R.O. (2003) Risk assessment: Replacing default options with specific science, Human and Ecological Risk Assessment, 9 (1), pp. 421-438.

McDonough W., Braungart M., Anastas P.T., Zimmerman J.B. (2003) Applying the Principles of Green Engineering to Cradle-to-Cradle Design, Environmental Science and Technology, 37 (23)

McDonough, W. (1992) The Hannover Principles, New York: William McDonough.

McDonough, W. and Braungart, M. (2002) Cradle to Cradle: Remaking the Way We Make Things, North Point Press, New York.

McGillivray, M. (1991). The Human Development Index: Yet Another Redundant Composite Development Indicator? World Development. Vol. 19. No. 10. pp. 1461-1468

McMichael A.J., Butler C.D., Folke C. (2003) New Visions for Addressing Sustainability, Science, 302 (5652), pp. 1919-1920.

Meadows, D. (1998). “Advice from abroad on restructuring electricity.” The Global Citizen. Bi-weekly column, September 17. Available at http://www.pcdf.org/meadows.

Meadows, D. (1998). Indicators and information for sustainable development. USA, The Sustainability Institute.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens (1972) The limits to growth, Universe Books, New York, New York, USA.

Meadows, D., J. Randers, and D. Meadows (2004) Limits to growth: the 30-year update, Chelsea Green, White River Junction, Vermont, USA.

MED (2006) Energy data file July 2005, G: Electricity, Ministry of Economic Development Available at: http://www.med.govt.nz/upload/28709/200507-g.pdf

Michell P.C.N., Quinn P., Percival E. Marketing strategies for mature industrial products (1991) Industrial Marketing Management, 20 (3), pp. 201-206.

Midgely, D.F. (1981) Toward a Theory of the Product Life Cycle: Explaining Diversity. Journal of Marketing 45 (Fall), pp. 109–115

Mihelcic JR, Crittenden JC, Small MJ, Shonnard DR, Hokanson DR, Zhang Q, Chen H, Sorby SA, James VU, Sutherland JW, Schnoor JL. (2003) Sustainability science and engineering: the emergence of a new metadiscipline. Environmental Science and Technology 37(23): 5314–5324.

Miles, M.B. and Huberman, A.M. (1994). Qualitative Data Analysis — An Expanded Sourcebook, Newbury Park: Sage.

Moffatt, I., Hanley, N. and Wilson, D. (2001) Measuring and modeling sustainable development, New York, The Parthenon Publishing Group

Molina, M and Rowland, F. (1974). "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone". Nature 249. pp. 810–2

Morales-Matamoros, O., Tejeida-Padilla, R., Badillo-Piña, I. (2010) Fractal behaviour of complex systems, Systems Research and Behavioral Science, 27 (1), pp. 71-86.

Morse, S. (2003). For better or for worse, till the human development index do us part? Ecological Economics, 45, 281–296.

Munasinghe, M. (2001) ‘The sustainomics trans-disciplinary meta-framework for making development more sustainable: applications to energy issues’, Int. J. Sustainable Development, Vol. 5, No. 1/2, pp. 125–182.

Munasinghe, Mohan and Adil Najam (2007) "Sustainomics and sustainable development." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published in the Encyclopedia of Earth April 29, 2007; Last revised May 7, 2007; Retrieved November 1, 2009]. <http://www.eoearth.org/article/Sustainomics_and_sustainable_development>

Munn, R. E. (1995) Atmospheric change in Canada: assessing the whole as well as the parts. Institute of Environmental Studies, University of Toronto

Munns Jr. W.R., Suter II G.W., Damstra T., Kroes R., Reiter L.W., Marafante E.(2003) Integrated risk assessment - Results from an international workshop, Human and Ecological Risk Assessment, 9 (1 SPEC. ISS.), pp. 379-386.

Munslow B., Ekoko F.E. (1995) Is democracy necessary for sustainable development? Democratization, 2 (2), pp. 158-178.

Murray, C. J. L. (1991). Development Data Constraints and the Human Development Index, Discussion Paper, United Nations Research Institute for Social Development, Geneva.

Musee, N., Lorenzen, L. (2007) Assessing sustainability of gold mining operations using fuzzy logic methodology, Australasian Institute of Mining and Metallurgy Publication Series, pp. 135-142

Myers N., Knoll A.H. (2001) The biotic crisis and the future of evolution, Proceedings of the National Academy of Sciences of the United States of America, 98 (10), pp. 5389-5392.

Narodoslawsky, M., Krotscheck, Ch., 2004. What can we learn from ecological valuation of processes with the sustainable process index (SPI)—the case study of energy production systems. J. Cleaner Prod. 12, 111–115.

National Research Council (2001) Committee on Geophysical and Environmental Data Staff (Contributor), Resolving Conflicts Arising from the Privatization of Environmental Data. Washington, DC, USA: National Academies Press, p 94.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L.(2007), Categorising tools for sustainability assessment, Ecological Economics, 60, 498–508.

Neumayer E. (2003) Weak versus strong sustainability: exploring the limits of two opposing paradigms. Second ed. Cheltenham: Edward Elgar.

Neumayer E. On the methodology of the ISEW, GPI, and related measures: Some constructive suggestions and some doubt on the threshold hypothesis. Ecol Econ 2000;34:347–61.

Nicolis, G. and Prigogine, I. (1989) Exploring Complexity, Freeman and Co., New York.

Nishiguchi, T. (2001) Coevolution of interorganizational relations Knowledge Emergence, pp. 197-222. I. Nonaka & T. Nishiguchi (Eds.), Oxford, UK: Oxford University Press.

Nishioka Y, Levy JI, and Norris GA. 2006. Integrating air pollution, climate change, and economics in a risk-based life cycle analysis: A case study of residential insulation. Hum Ecol Risk Assess 12(3)

Nishioka Y, Levy JI, Norris GA, et al. 2002. Integrating risk assessment and life cycle assessment: A case study of insulation. Risk Anal 22:1003–17

Nishioka Y., Levy J.I., Norris G.A., Wilson A., Hofstetter P., Spengler J.D. (2002) Integrating risk assessment and life cycle assessment: A case study of insulation, Risk Analysis, 22 (5), pp. 1003-1017.

Niven K., McLeod R. (2009) Offshore industry: Management of health hazards in the upstream petroleum industry, Occupational Medicine, 59 (5), pp. 304-309.

Noble, B.F. (2000) Strategic Environmental Assessment: what is it & what makes it strategic? J Environ Assess Policy Manag, 2 (2), pp. 203-224.

Nonaka, I. and Nishiguchi, T. (2001) Knowledge Emergence: Social, Technical, and Evolutionary Dimensions of Knowledge Creation. Oxford, UK: Oxford University Press.

Norberg, J. and Cumming, G. S. (2008) Eds. Complexity Theory for a Sustainable Future; Columbia University Press: New York

Norman, W. and MacDonald, C. (2004) Business Ethics Quarterly Getting to the bottom of "Triple Bottom Line" Volume 14, Issue 2, April, Pages 243-262+345

Norris, G.A. (2001) Integrating life cycle cost analysis and LCA, International Journal of Life Cycle Assessment, 6 (2), pp. 118-120.

NRC (1999) Our Common Journey: A Transition Toward Sustainability. National Research Council Board on Sustainable Development Washington, DC: National Academy Press.

Nyström, M. (2006) Redundancy and response diversity of functional groups: implications for the resilience of coral reefs. Ambio 35 (1),30–35.

O2 (2007) Allocation in Recycling – Online LCA Forum discussion initiated by the author, Available at: www.lca-net.com/files/recycling.pdf Last accessed: 04/03/2010.

O'Brian M, Doig A, Clift R (1996): Social and Environmental Life Cycle Assessment (SELCA). Int J LCA 1 (4) 231-237

Odum HT. (1988) Self organisation, transformity, and information. Science 242:1132–9.

Odum, E. P. (1993) Ecology and our endangered life support systems, Second edition, Sinauer, Sunderland, Massachusetts, USA.

Odum, H.T. (1996) Environmental Accounting: Emergy and Environmental Decision Making. New York: John Wiley and Sons

Ogden P., Podesta J., Deutch J. (2008) A new strategy to spur energy innovation, Issues in Science and Technology, 24 (2), pp. 35-44.

Oki, T. (2010) Issues on water footprint and Beyond, Institute of Industrial Science, The University of Tokyo, Consultative Workshop on Water Footprint, Neutrality and Efficiency, Global Environmental Centre Foundation, Japan, June 3rd, 2010 Available at: http://gec.jp/gec/en/Activities/ietc/fy2010/wf/wf_os-3e.pdf

Onisto, L. (1999) The business of sustainability, Ecological Economics, 29: 37-43

Orr D.W. (2002) Four challenges of sustainability, Conservation Biology, 16 (6), pp. 1457-1460

Ott, E. (1993) Chaos in Dynamical Systems, Cambridge University Press, New York.

Packard, V. (1961) The Waste Makers, London, UK: Longmans Green and Co.

Pant R, van Hoof G, Schowanek D, et al. 2004. Comparison between three different LCIA methods for aquatic ecotoxicity and a product environmental risk assessment: Insights from a detergent case study within OMNIITOX. Internat J LCA 9(5):281–342

Parris T.M., Kates R.W. (2003) Characterizing and measuring sustainable development, Annual Review of Environment and Resources, 28, pp. 559-586.

Pascale, R. T. (1999) Surfing the edge of chaos, Sloan Management Review, 40(3): 83

Pearce D. (1997) Substitution and sustainability: some reflections on Georgescu–Roegen. Ecol Econ ;22:295–7.

Pearce, D. (1987) Foundations of an Ecological Economics. Ecological Modelling, 38 (1-2): 9-18.

Pearce, D.W., Atkinson, G. (1993) Capital theory and the measurement of sustainable development: an indicator of weak sustainability. Ecol. Econ. 8, 103–108.

Peet, J. and Bossel, H (2000) 'An ethics-based systems approach to indicators of sustainable development', International Journal of Sustainable Development, 3(3): 221-238

Peet, J. and H. Bossel, (1999) Ethics as the grounding of a new paradigm of ecological economics for community. ANZSEE Conference, Brisbane, Australia, 5-7 July, 1999.

Peitgen, H.O., Jurgens, H., Saupe, D. (1992) Chaos and Fractals: New Frontiers of Science, Springer, New York

Peterson, G.D. (2002) Estimating resilience across landscapes, Conservation Ecology 6 (1), 17 [online] URL: http://www.consecol.org/vol6/iss1/art17.

Peterson, G.D., Carpenter, S.R., Brock, W.A. (2003) Uncertainty and the management of multistate ecosystems: an apparently rational route to collapse. Ecology 84 (6), 1403–1411.

Phillis Y.A., Davis B.J. (2009) Assessment of corporate sustainability via fuzzy logic, Journal of Intelligent and Robotic Systems: Theory and Applications, 55 (1), pp. 3-20.

Phillis, Y. and Andriantiatsaholinianina, L. (2001) Sustainability: an ill-defined concept and its assessment using fuzzy logic, Ecological Economics, 37(3):435-456.

Phillis, Y. and Kouikoglou, V. (2009) Fuzzy measurement of sustainability, Nova Science Publishers, Inc.: New York

Plastics New Zealand (2006) Plastics mass balance survey (2005). Available at:http://www.plastics.org.nz/page.asp?id=500, Retrieved: 15/10/2006

Plowman, D.A., Solansky, S., Beck, T.E., Baker, L., Kulkarni, M., Travis, D.V. (2007) The role of leadership in emergent, self-organization, Leadership Quarterly, 18 (4), pp. 341-356.

Pope III C.A., Burnett R.T., Thun M.J., Calle E.E., Krewski D., Ito K., Thurston G.D. (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, Journal of the American Medical Association, 287 (9), pp. 1132-1141.

Pope, J., Annandale, D., Morrison-Saunders, A. (2004) Conceptualising sustainability assessment, Environmental Impact Review, 24, 595 – 616.

Pope, J., Morrison-Saunders, A., Annandale, D. (2005) Applying sustainability assessment models, Impact Assessment and Project Appraisal 23 (4), pp. 293-302

Porter, T. (2006). Coevolution as a research framework for organizations and the natural environment. Organization and Environment, 19, 479-504.

Potting, J. and Hauschild, M.: Background for spatial differentiation in life cycle impact assessment – the EDIP2003 methodology. Environmental project no. ¤¤, Danish Environmental Protection Agency, Copenhagen, 2004 (in press).

PRé Consultants (2006) SimaPro v. 7.0. Amersfoort, The Netherlands

Prescott-Allen, R., 2001. The Wellbeing of Nations. Island Press, Washington, DC.

Prigogine, I. and I. Stengers (1984). Order Out of Chaos. New York: Bantam Books.

Punch, K. F. (1998) Introduction to Social Research, Sage, London

Rammel C., Stagl S., Wilfing H.(2007) Managing complex adaptive systems - A co-evolutionary perspective on natural resource management, Ecological Economics, 63 (1), pp. 9-21.

Raskin P, Banuri T, Gallopin G, Gutman P, Hammond A, Kates R and Swart R. (2002) Great Transition: The Promise and Lure of the Times Ahead. Stockholm Environment Institute, Stockholm.

Reap J., Roman F., Duncan S., Bras B. (2008a) A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis, International Journal of Life Cycle Assessment, 13 (4), pp. 290-300.

Reap J., Roman F., Duncan S., Bras B. (2008b) A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation, International Journal of Life Cycle Assessment, 13 (5), pp. 374-388.

Rebitzer G (2002): Integrating Life Cycle Costing and Life Cycle Assessment for Managing Costs and Environmental Impacts in Supply Chains. In: Seuring S, Goldbach M (Eds): Cost Management in Supply Chains. Physica-Verlag, Heidelberg, p 128-146

Rebitzer, G. and Jolliet, O. (2005) Defining LCA System Boundaries Based on Unit Process Specific Cut-offs and on Input-Ouput, SETAC 26th Annual Meeting in North America, Environmental Science in a Global Society: SETAC's Role in the Next 25 Years, 13-17 November, Baltimore, Maryland, USA Abstract available at: http://abstracts.co.allenpress.com/pweb/setac2005/document/57420

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., (...), Pennington, D.W. (2004) Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environment International, 30 (5), pp. 701-720.

Rees, W. And M Wackernagel (1996) Urban ecological footprints: why cities cannot be sustainable – and why they are a key to sustainability, Environmental Impact Assessment Review, 16: 223-248

Regnier E. (2007) Oil and energy price volatility, Energy Economics, 29 (3), pp. 405-427.

Reinert, K.H., Jayjock, M.A., Weiler, E.D. (2006) Using risk assessment to facilitate and enhance the movement to sustainability, Environmental Quality Management 15 (3), pp. 1-8

Renn, O, 1998: Three Decades of Risk Research: Accomplishments and new Challenges, Journal of Risk Research, Vol. 1, pp. 49-71

Richards, L. (1993). “Writing a Qualitative Thesis or Grant Application”. In So Where’s Your Research Profile? A Resource Book for Academics. K. Beattie ed. South Melbourne: Union of Australian College Academics.

Rihani, S. (2002) Complex Systems Theory and Development Practice, New York: Zed books.

Risbey J., Kandlikar M., Patwardhan A. (1996) Assessing integrated assessments, Climatic Change, 34 (3-4), pp. 369-395.

Robert, K.-H. (2000). “Tools and concepts for sustainable development, how do they relate to a general framework for sustainable development, and to each other?” Journal of Cleaner Production 8: 243-254.

Roberts, P., Priest, H. and Traynor, M. (2006) Reliability and validity in research, Nursing standard (Royal College of Nursing (Great Britain): (1987), 20 (44), pp. 41-45.

Robinson, J. B. (2004) Squaring the circle? Some thoughts on the idea of sustainable development. Ecological Economics, 48(4), 369-384.

Robson, C. (1993) Real World Research. Blackwell, Oxford

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley (2009) Planetary boundaries:exploring the safe operating space for humanity, Ecology and Society, 14(2): 32. [online] URL: http://www.ecologyandsociety.org/vol14/iss2/art32/

Rosenberg, B. (2005) Case Study of Interface Carpet and Fabric Company. http://www.chemicalspolicy.org/downloads/InterfaceCaseStudy4.pdf

Rosenberg, B. (2005) Case study of Interface Carpet and Fabric Company, Tufts University Department of Public Health and Family Medicine

Ross S., Evans D. (2002) Excluding site-specific data from the LCA inventory: How this affects life cycle impact assessment, International Journal of Life Cycle Assessment, 7 (3), pp. 141-150.

Ross, D. T. (1977) Structured analysis (SA): A language for communication ideas. IEEE Transactions on Software Engineering 3(1): 16–35.

Rotmans J., Van Asselt M., Anastasi C., Greeuw S., Mellors J., Peters S., Rothman D., Rijkens N. (2000) Visions for a sustainable Europe, Futures, 32 (9), pp. 809-831.

Rowe, G., and Wright, G. (2001). Differences in expert and lay judgments of risk: myth or reality? Risk Analysis, 21, 341-356.

Sadler, B (1999), "A framework for environmental sustainability assessment and assurance", in J Petts (editor), Handbook of Environmental Impact Assessment, vol 1 (Blackwell Science, Oxford) pages 12–32.

Sadorsky P. (1999) Oil price shocks and stock market activity, Energy Economics, 21 (5), pp. 449-469.

Sagar, A. D., & Najam, A. (1998). The human development index: a critical review. Ecological Economics, 25, 249–264.

Sandholzer D., Narodoslawsky M. (2007) SPIonExcel-Fast and easy calculation of the Sustainable Process Index via computer, Resources, Conservation and Recycling, 50 (2), pp. 130-142.

Sawyer, R. K. (2005). Social Emergence: Societies as Complex Systems. New York. Cambridge, University Press.

Scheffer M., Carpenter S.R. (2003) Catastrophic regime shifts in ecosystems: Linking theory to observation, Trends in Ecology and Evolution, 18 (12), pp. 648-656.

Schellnhuber, H.J., Crutzen, P.J., Clark, W.C., Claussen, M., Held, H. (2004) Earth System Analysis for Sustainability. Cambridge, MA: MIT Press

Schmidt, W., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschamann, D., Pichon, S., Thiel, Ch. (2004) Life Cycle Assessment of lightweight and end of life scenarios for generic compact class passenger vehicle, International Journal of LCA, 9(6):405-416

Schmidt, W.-P., Taylor, A. (2006) Ford of Europe's Product Sustainability Index, Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, Available at: www.mech.kuleuven.be/lce2006/key2.pdf

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 779-810.

Schröder, A., Persson, L., De Roos, A.M., 2005. Direct experimental evidence for alternative stable states: a review.Oikos 110 (1), 3–19.

Schumacher, E. (1973) Small is Beautiful: Economics as if People Matter, London: Abacus.

Scienceman DM. (1987) Energy and emergy. In: Pillet G, Murota T, editors. Environmental economics: the analysis of amajor interface. Geneva:Rolland Leimgruber. p. 257–76.

Sciubba E, and Ulgiati S. (2005) Emergy and exergy analyses: complementary methods or irreducible ideological options? Energy 30:1953–88.

Scrase, J.I. and Sheate, W.R. (2002) 'Integration and integrated approaches to assessment: what do they mean for the environment?', Journal of Environmental Policy and Planning, Vol. 4, No. 4, pp.275–294.

Scriven, M 1991, The evaluation thesaurus, 4th edn, Sage, Thousand Oaks, California

Senbel M., McDaniels T., Dowlatabadi H. (2003) The ecological footprint: A non-monetary metric of human consumption applied to North America, Global Environmental Change, 13 (2), pp. 83-100.

SETAC (1991). A Technical Framework for Life Cycle Assessments. Society for Environmental Toxicology and Chemistry, Washington, D.C.

SETAC (1993) Guidelines for Life Cycle Assessment: A 'Code of Practice.' Society of Environmental Toxicology and Chemistry. Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A.A., Oude, N., Parrish, R., Perriman, R., Postlethwaite, D., Quay, B., Seguin, J., and Vigon, B. (eds).

Shapiro KG (2001): Incorporating Costs in LCA. IntJ LCA 6 (2) 121-123

Shatkin J.A. (2008) Informing environmental decision making by combining life cycle assessment and risk analysis, Journal of Industrial Ecology, 12 (3), pp. 278-281.

Shell International (1998). The Shell Report 1998: Profits and principles - does there have to be a choice? http://www.shell.com/shellreport.

Shuttleworth, M. (2008) Validity and Reliability. Retrieved [Date of Retrieval] from Experiment Resources: http://www.experiment-resources.com/validity-and-reliability.html

Sidle, R.C., Taylor. D., Lu, X.X., Adger, W.N., Lowe, D.J., de Lange, W.P., Newnham, R.M., Dodson, J.R. (2004) Interactions of natural hazards and society in Austral-Asia: Evidence in past and recent records, Quaternary International, 118-119, pp. 181-203.

Simmons, L.M. (1997) The business of Complexity: Understanding research on complex adaptive systems, Presentation at Santa Fe Centre for Emergent Strategies. Santa Fe, New Mexico

Simon, H. A. (1962) The Architecture of Complexity. Proceedings of the American Philosophical Society, 106(6), 467-482.

Sippe, R. (1999). Criteria and Standards for Assessing Significant Impact. In Petts, J. (1999) (Ed). Handbook of Environmental Impact Assessment Volume 1

Skander, A., L. Roucoules, and J. S. K. Meyer (2008) Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design. International Journal of Advanced Manufacturing Technology 37(5–6): 443–454.

Skelton, R. (1996) Process safety analysis: an introduction, The Institute of Chemical Engineers, Rugby, England

Slovic P., Finucane M.L., Peters E., MacGregor D.G. (2004) Risk as Analysis and Risk as Feelings: Some Thoughts about Affect, Reason, Risk, and Rationality, Risk Analysis, 24 (2), pp. 311-322.

Slovic, P. (1992). Perception of risk: reflections on the psychometric paradigm. In S. Krimsky and D. Golding (Eds.), Social theories of risk (pp. 117-152). Westport, CT: Praeger.

Smith V.K. (2008) Risk perceptions, optimism, and natural hazards, Risk Analysis, 28 (6), pp. 1763-1767.

Snowden, David J., and Mary E. Boone. "A Leader's Framework for Decision Making." Harvard Business Review, November 1, 2007: 69-76.

Solow RM. (1993) An almost practical step towards sustainability. Resour Policy, 19:162–72.

Sonnemann, G., Schuhmacher, M. and Castells. F. (2004) Integrated Life-Cycle and Risk Assessment for Industrial Processes, CRC Press

Sonnemann, G., Castells, F. and Schuhmacher, M. (2004) Integrated Life cycle and risk assessment for industrial processes, CRC Press LLC, New York

Spitzley, D., Dietz, B. and Keoleian, G. (2006) Life-Cycle Assessment of Office Furniture Products, Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan, Ann Arbor. Available at: http://css.snre.umich.edu/css_doc/CSS06-11.pdf

Stacey, R.D. (1995) The science of complexity: An alternative perspective of strategic change process, Strategic Management Journal, 16(6):477-495

Stern, N. (2007) The Economics of Climate Change: The Stern Review, Cabinet Office. HM Treasury. Available from: http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm (accessed 06/02/07).

Stevens, C. (2005). Measuring sustainable development. Paris: Organisation for Economic Co-operation and Development.

Stranddorf H, Hoffmann L, Schmidt A (2005) Impact categories, normalisation and weighting in LCA. Environmental News no. 78 from the Danish Environmental Protection Agency, Copenhagen

Stranddorf, H.K., Hoffmann, L. & Schmidt, A. (2005) Update on impact categories, normalisation and weighting in LCA. Environmental Project no. 995, Danish EPA, 2005.

Suter II G.W., Vermeire T., Munns Jr. W.R., Sekizawa J.(2003) Framework for the integration of health and ecological risk assessment, Human and Ecological Risk Assessment, 9 (1 SPEC. ISS.), pp. 281-301.

Szargut J, Morris DR, Steward FR. (1988) Exergy analysis of thermal, chemical andmetallurgical processes. NewYork: Hemisphere Publishing

Taylor, R., Frame, B., Delaney, K. and Brignall-Theyer, M. (2007), Four Futures for New Zealand, 2nd edition, Manaaki Whenua Press, Lincoln, NZ.

Teisman, G. and J. Edelenbos (2004) Getting through the 'twilight zone'" managing transitions through process-based, horizontal and interactive governance in Elzen, B., Geels, F. And Green, K (2004) System innovation and the transition to sustainability theory, evidence and policy, Cheltenham, UK ; Northhampton, MA, USA : Edward Elgar.

The Natural Step. Sustainability made easy: guide for logical living. The Natural Step Environmental Institute Australia, Melbourne, Australia; 2001.

Therivel, R. (1993) Systems of Strategic Environmental Assessment, Environmental Impact Assessment Review, 13 (3): 145-168

Therivel, R. and Partidario, M. (1996) The Practice of Strategic Environmental Assessment. Earthscan Publications Limited. UK.

Therivel, R., Wilson, E., Thompson, S., Heaney, D. & Pritchard, D. (1992) Strategic Environmental Assessment. Earthscan Publications Limited, London.

Tilman D. and Lehman C. (2001) Human-caused environmental change: Impacts on plant diversity and evolution, Proceedings of the National Academy of Sciences of the United States of America, 98 (10), pp. 5433-5440.

Towne, L. (Editor) and Shavelson, Richard J. (Editor); (2002) National Research Council Staff. Scientific Research in Education, Washington, DC, USA: National Academies Press, p 52.

Tukker, A. (2000) Life cycle assessment as a tool in environmental impact assessment, Environmental Impact Assessment Review, 20 (4), pp. 435-456.

Tukker, A., Charter, M., Vezzoli, C., Stø, E and Maj Munch Andersen (2008) System Innovation for Sustainability 1: Perspectives on Radical Changes to Sustainable Consumption and Production, Sheffield, UK : Greenleaf Pub.

Tukker, A., Charter, M., Vezzoli, C., Stø, E and Maj Munch Andersen (2008) System Innovation for Sustainability 1: Perspectives on Radical Changes to Sustainable Consumption and Production, Sheffield, UK : Greenleaf Pub.

Udo de Haes, H. (1993) Applicationof life cycle assessment: expectations, drawbacks and perspectives, Journal of cleaner Production, 1 (3-4): 131-137

Udo de Haes, H., Heijungs R, Huppes G, et al. (2000) Full mode and attribution mode in environmental analysis. J Ind Ecol 41:45–56

Udo de Haes, H., Sleeswijk A.W., Heijungs R. (2006) Similarities, differences and synergisms between HERA and LCA - An analysis at three levels, Human and Ecological Risk Assessment, 12 (3), pp. 431-449.

Udo De Haes, H.A., Heijungs R., Suh S., Huppes G. (2004) Three strategies to overcome the limitations of life-cycle assessment, Journal of Industrial Ecology, 8 (3), pp. 19-32.

Ulgiati S, Raugei M, Bargigli S. (2006) Overcoming the inadequacy of single criterion approaches to Life Cycle Assessment. Ecol Model, 190:432–42.

UN (1999) Agenda 21, United Nations, Available at: http://www.un.org/esa/dsd/agenda21/res_agenda21_00.shtml

UNEP (2002) Global Environmental Outlook 3: Past, Present and Future Perspective, United Nations Environmental Protection EarthPrint Ltd. Available from: http://www.grida.no/geo/geo3/english/pdf.htm (accessed 08/02/07).

UNGA (1982) World Charter for Nature, Resolution 37/7

Upham, P. (2000) An assessment of The Natural Step theory of sustainability, Journal of Cleaner Production, 8(6): 445-454

Upham, P. (2000) Scientific consensus on sustainability: the case of The Natural Step. Sustainable Development 8:180–190.

US Census Bureau (2010) International Data Base (IDB) Available at: http://www.census.gov/ipc/www/idb/worldpopinfo.php Last retrieved: July, 2010

van Eijnatten, F.M., Putnik, G.D. and Sluga, A. (2007) “Chaordic systems thinking for novelty in contemporary manufacturing”, CIRP Annals, Vol. 56 No. 1, pp. 447-50.

Vanclay F. The Triple Bottom Line and Impact Assessment: how do TBL, EIA, SIA, SEA and EMS relate to each other? J Environ Assess Policy Manag 2004;6(3):265–88 (September 2004).

Verheem, R. (2002), Strategic Environmental Assessment: Performance Criteria. Developed for the International Association of Impact Assessment (IAIA) in consultation with SEA-section. Available online: http://www.iaia.org/Members/Publications/Special_Pubs/sp1.pdf [visited 12.02.2007]

Voinov A. (2008) Understanding and communicating sustainability: Global versus regional perspectives Environment, Development and Sustainability, 10 (4), pp. 487-501.

Von Seht, H. (1999) Requirements of a comprehensive strategic environmental assessment system, Landscape Urban Plan 45: 1-14

Wackernagel, M. (1998) The ecological footprint of Santiago de Chile, Local Environment, 3 (1), pp. 7-25.

Wackernagel. M., and Rees, W. (1996) Our Ecological Footprint: Reducing human impact on the Earth, New Society Publishers, Gabriola Island, BC

Waldrop, M.M. (1992) Complexity: The Emerging Science at the Edge of Chaos and Order,Simon and Schuster, New York, NY.

Walker, B. and J. A. Meyers (2004) Thresholds in ecological and social–ecological systems: a developing database. Ecology and Society 9(2): 3. [online] URL: http://www.ecologyandsociety.org/vol9/iss2/art3/

Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A. (2004) Resilience, adaptability and transformability in social-ecolological systems. Ecology and Society 9 (2), art. 5. http//www.ecologyandsociety.org/vol9/iss2/art5

Washington-Allen, R. A., R. D. Ramsey, N. E. West, and B. E. Norton (2008) Quantification of the ecological resilience of drylands using digital remote sensing, Ecology and Society 13(1): 33. [online] URL: http://www.ecologyandsociety.org/vol13/iss1/art33/

WCED (World Commission on Environment and Development), (1987) Our Common Future, Oxford University Press, Oxford.

Weaver, P.M. and Rotmans, J. (2006) ‘Integrated sustainability assessment: what is it, why do it and how?’, Int. J. Innovation and Sustainable Development, Vol. 1, No. 4, pp.284–303.

WEF (2005) Environmental Sustainability Index, Available at: http://www.yale.edu/esi/ESI2005_policysummary.pdf Last access: 05/06/2010

Wegener Sleeswijk A, Heijungs R, and Erler ST. 2003. Risk assessment and life-cycle assessment: Fundamentally different yet reconcilable. Greener Management International 41:77–87

Weidema BP. (2001) Avoiding co-product allocation in life-cycle assessment. Journal of Industrial Ecology;4:11 – 33.

Weigel, K. (1991) Replacing chlorofluorocarbons in industry, Journal of the IES, 33 (6): 23-26

Wenzel H, Hauschild M, Ahing L (1997) Environmental Assessment of Products. Vol. 1 - IXlethodolog% tools and case studies in product development. First edition. Chapman & Hall, United Kingdom, Kluwer Academic Publishers, Hingham, MA. LISA. ISBN 0-412-80800-5

Wenzel, H., Hauschild, M.Z., Alting, L., (1997) Environmental Assessment of Products. Methodology, Tools, Techniques and Case Studies, vol. 1. Chapman & Hall, United Kingdom, Kluwer Academic Publishers, Hingham, MA, USA, 544 pp. ISBN 0 412 80800 5.

Wheatley, M. J. (1992) Leadership and the new science, Barrett-Kochler, San Francisco

White, A., Savage, D., Shapiro, K. (1996): Life-Cycle Costing: Concepts and Application. Chapter 7. In: Curran, Mary Ann (Ed): Environmental Life-Cycle Assessment, McGraw-Hill, New York, p 7.1-7.19

Wildavsky, A., and Dake, K. (1990). Theories of risk perception: Who fears what and why? Daedalus, 119(4), 41-60.

Wilkinson P., Smith K.R., Joffe M., Haines A. (2007) A global perspective on energy: health effects and injustices, Lancet, 370 (9591), pp. 965-978.

Wilson, E. B. (1952) An Introduction to Scientific Research, McGraw-Hill.

Wilson, J. andGrant, J. L.(2009) 'Calculating ecological footprints at the municipal level: what is a reasonable approach for Canada?', Local Environment, 14: 10, 963 — 979

World Bank (2002) Manual for Calculating Adjusted Net Savings, Bolt, K., Matete, M. and Clemens, M. Environment Department. Available at: http://siteresources.worldbank.org/INTEEI/1105643-1115814965717/20486606/Savingsmanual2002.pdf

Wright H.E., Zhang Q., Mihelcic J.R. (2008) Integrating economic input-output life cycle assessment with risk assessment for a screening-level analysis, International Journal of Life Cycle Assessment, 13 (5), pp. 412-420.

Wright, R. (2005) A Short History of Progress, New York: Carroll & Graf Publishers.

Wrisberg, N., H. A. Udo de Haes, U. Triebswetter, P. Eder, and R. Clift (eds.) (2002) Analytical tools for environmental design and management in a systems perspective; the combined use of analytical tools. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Zickfeld, K. and T. Bruckner, 2003: Reducing the risk of abrupt climate change: emissions corridors preserving the Atlantic thermohaline circulation. Integrated Assessment Journal, 4, 106-115.

Zimmerman, B., Lindberg, C., Plsek, P. (1998) Edgeware. VHA, Irving, TX.

Zimmermann, H. (1996) Fuzzy set theory and its applications, Kluwer Academic Publishers, Boston

APPENDIX A

Environmental Performance Questionnaire

For manufacturers and distributors of building materials, products, systems and services.

DETAILS OF MANUFACTURER AND PRODUCT:

Manufacturer Details:

Company Name:

Street Address:	Postal Address:	Phone:	Manufacturing Site Street Address:
City/Town:	City/Town:	Fax:	City/Town:
Country:	Country:	Web:	Country:

Product Information:

Function(s):	Brand:	Product:

Respondent's Details:

Contact Name:	Position:	Phone:
Fax:	Email:	

Please note that if you have any queries regarding this questionnaire or need some assistance, please do not hesitate to contact Gaya (gayag@formway.com). Some sections may be difficult to fill in so please supply as much information as possible.

Embodied Materials and Energy, and Associated Environmental Impacts

The embodied energy and materials are the total amount of energy and materials required to produce the particular product from raw materials and transport it to the building site. They include the energy and materials necessary for mining and harvesting basic inputs, transformation and manufacturing, and transport and packaging throughout the supply chain.

The environmental impact of such activities can be reduced through materials and energy efficiency, use of renewable energy and materials harvested sustainably, cleaner production and the use of low-toxicity materials, the use of recycled materials and so on.

A YOUR MANUFACTURING PROCESS

Materials

A1 Is scrap material from your process re-used, or recycled? Yes/No

If yes, please identify the material(s), whether it is re-used/recycled in your process or recycled by another user, and what percentage of the material in your product this represents:

Material	Used by you (%)	Used by Others (%)

A2 Are any **non-hazardous** solid materials disposed of to landfill from your process? Yes/No

If yes, please indicate the total amount landfilled (in kg/kg of product or in kg/item of product – specify which):

_______________ kg/_____ of product

Please provide as much detail as you can on the composition of this landfilled solid waste:

Material	% by weight of landfilled solid waste

A3 Water

Is water used in the manufacturing process? Yes/No

If yes, how much water is required in manufacturing (in L/kg of product, or in L/item of product – specify which):

__________L/ ______ of product

Have specific *in-plant* water efficiency or water re-use/recycling measures been implemented? Yes/No

If yes, please describe the measures indicating when they were introduced and the savings in water consumption (in L/kg of product or L/item of product - specify which) that have resulted.

Measure	When Implemented	Savings

A4 Energy

Please specify the energy use per kg or per item of product from each of the following energy sources if applicable:

Electricity	kWh/
Natural Gas	MJ/
Diesel	Litres/
LPG	Litres/
Biomass (specify- wood/straw etc)	kg/
Other (specify)	/

If electricity is used what is its source?

The Grid	%	
Certified Green Power	%	Supplier
Own generation	%	

If you generate your own electricity, please indicate the fuel(s) used and the estimated generation efficiency:

Fuel	Generation Efficiency

Have specific in-plant energy efficiency measures been implemented?
Yes/No

If yes, please describe the measures indicating when they were introduced and savings in energy consumption (in MJ/kg or MJ/item of product) that have resulted.

Measure	When Implemented	Savings

A5 Greenhouse Gases

Do emissions of direct greenhouse gases occur in the manufacturing process (Please see Appendix A for a list of greenhouse gases)? Yes/No

If yes, if possible please identify the gases, and the nature, source and scale (in kg of the gas concerned/kg or item of product – specify which) of the emissions:

Greenhouse Gas	Nature, Source and Scale of Emissions

Are any steps planned to reduce such emissions?: Yes/No

If yes, please describe the emission being addressed, the planned measure(s) and its timing, and the anticipated impact (quantified if possible):

Greenhouse Gas	Measure and Timing	Anticipated Impact

Have you calculated the embodied greenhouse gas emissions associated with the manufacture of your product? Yes/No

If yes, what is it (in kg CO_2-e/kg of material or kg CO_2-e/item of product)?
___________kg CO_2-e/____ of product

In addition to energy efficiency measures, if you have switched from more to less carbon-intensive fossil fuels or to renewable energy, has carbon dioxide emissions been reduced? Yes/No

If yes, please describe the measures indicating when they were introduced and the reductions in carbon dioxide emissions (in MJ/kg or MJ/item of product) that have resulted.

Measure	When Implemented	Reduction in CO_2 achieved

A6 Ozone Depletion

Is use of the following ozone-depleting gases (chlorofluorocarbon (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl chloroform (1,1,1-trichloroethane – $C_2H_3Cl_3$), methyl bromide (CH_3Br) carbon tetrachloride (CCl_4) associated with the manufacturing process? Yes/No/Don't Know

Are there any associated emissions of these gases? Yes/No/Don't Know

If yes, please identify the gases and the nature, source and scale of any emissions (in kg of the gas concerned/kg of input material):

Input Material	Ozone-Depleting Gas	Nature, Source and Scale of Emissions

A7 Hazardous Substances Inputs and Releases to the Environment

Appendix B contains the 90 substances (or classes of substances) listed on Australia's National Pollutant Inventory whose release into the environment must be reported on from 2001/2002 onward.

Are any of the substances in Appendix B used in your manufacturing process? Yes/No

If yes, please indicate which substances are used and the reason for using them:

Hazardous Substance	Reason for using substance

During manufacture are any of the substances in Appendix A released to or deposited in

(i) Air

(ii) Surface water bodies

(iii) Aquifers

(iv) Sewer

(v) Landfill

(vi) Storage facilities? Yes/No

If yes, please indicate which substances, the manner of their release or deposition, and the quantity involved (in kg/kg of product or kg/item of product – specify which):

Substance	Manner of Release or Deposition	Quantity

Do you have specific plans in place to strive towards zero pollution from the manufacturing process? Yes/No

If yes, please provide details:

Substance(s)	Measure and Timing	Anticipated Impact

A8 Other

In addition to the above, have any other actions been taken to lessen the environmental impact of the manufacturing process? Yes/No

If yes, please describe and quantify the benefit if possible:

Action	Benefit

B RAW MATERIALS TO YOUR MANUFCATURING PROCESS

You may find this section of the questionnaire difficult to fill in. If you are able to provide information here, please provide some details of the mechanism you used to gain this information:

NB. The input material refers to the input materials required to make a product by Formway. I.e. the product that <u>you</u> supply to Formway Furniture (or alternatively to your customer who then supplies it to Formway)

B1 Do you know the amount of raw material required to produce a kilogram input material into your plant. Please specify the nature of the raw material where possible (eg for metals - are they in ore, or based on metal content only)? Yes/No

If yes, please indicate the material(s) and weight of original material:

Input Material (eg. Aluminium, nylon etc)	Weight of Original Material to Produce a kg of Input Material (kg)

B2 Is any of the material that does not become an input to your plant put to another beneficial use[i]? Yes/No/Don't Know

If yes, please indicate the materials, describe the beneficial use, and the amount of material so used per kg of your input material.

Input Material	Description of Beneficial Use(s)	Weight of Material Used per kg of Input Material (kg)

B3 **Water**

Do you know how much water is required (the embodied water) to acquire the input materials to? Yes/No/NA

If yes, please indicate the input material and the embodied water in standard units (eg, L/kg of material)

Input Material	Embodied Water

Have steps been taken to minimise the amount of water used to supply inputs for manufacture, either through water efficiency measures or wastewater recycling? Yes/No/Don't Know

If yes, please provide details:

Input Material	Measure	Water Reduction Achieved per kg of Input Material

B4 Energy

Do you know the embodied energy of the input material? Yes/No

If yes, please indicate the material(s) and its embodied energy in standard units (eg, MJ/kg of material).

Input Material	Embodied Energy

If you know whether the embodied energy figures include the following energy sources please indicate:

Feedstock energy (eg oil into plastic polymers)? Yes/ No/Don't know

Renewable energy (eg solar, hydro, biomass)? Yes/ No/Don't know

If yes, please provide a description of the type of renewable energy used and how and where it is used in your supply chain:

Have steps been taken to minimise the amount of energy used to supply inputs into the manufacturing process? Yes/No/Don't Know

If yes, please provide details:

Input Material	Measure	Energy Reduction Achieved per kg of Input Material

B5 Greenhouse Gases

Do you know the embodied greenhouse gas emissions of the input material? Yes/No

If yes, please indicate the material(s) and its embodied greenhouse gas emissions in standard units (eg, kg CO_2-e/kg of material)

Input Material	Embodied Greenhouse Gas Emissions

In addition to energy efficiency measures, if you have switched from more to less carbon-intensive fossil fuels or to renewable energy, has carbon dioxide emissions been reduced? Yes/No

If yes, please identify the measure and the emissions reduction achieved:

Input Material	Measure	Reduction in CO_2/kg Material Achieved

Are emissions of any greenhouse gases associated with supplying inputs into the manufacturing process (Please see Appendix A for a list of greenhouse gases)? Yes/No/Don't Know

If yes, if possible please identify the gases, and the nature, source and scale (in kg of the gas concerned/kg of input material) of the emissions:

Input Material	Greenhouse Gas	Reduction in CO_2 emissions/kg material achieved

Are any steps planned to reduce such emissions?: Yes/No

If yes, please describe the emission being addressed, the planned measure(s) and its timing, and the anticipated impact (quantified if possible):

Emission	Measure and Timing	Anticipated Impact

B6 Transport

For the input material, please indicate the transport mode(s) used and the distance(s) travelled to your factory gate:

Input Material	Road (km)	Rail (km)	Sea (km)	Air (km)

If embodied energy and embodied greenhouse gas emission values have been provided in B4 and B5, did these include an allowance for transport? Yes/No/Not Applicable

If yes, please indicate which substances, the manner of their release or deposition, and the quantity involved (in kg/kg of input material):

Input Material	Hazardous Substance	Manner of Release or Deposition	Quantity (kg/kg)

B8 Other

Have any other actions been taken to lessen the environmental impact of the supply of input materials to the manufacturing process? Yes/No/Don't Know

If yes, please describe and quantify the benefit (per kg of input material) if possible:

Input Material	Beneficial Action	Benefit

C ENVIRONMENTAL POLICY

C1 Does your company have any environmental policy plans implemented? Yes/No

If yes, please attach a copy of the plan to this questionnaire.

C2 Is there an environmental management plan implanted for your manufacture process of the input material? Yes/No

If yes, please attach a copy of the plan to this questionnaire.

C3 Are these environmental policy and management plans certified by anyone or any organisation? Yes/No/Not applicable

THE END

If no, and transport impact values are available, please indicate them here (with units):

Input Material	Embodied Energy due to Transport	Embodied Greenhouse Gas Emissions due to Transport

B6 Ozone Depletion

Is use of the following ozone-depleting gases (chlorofluorocarbon (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl chloroform (1,1,1-trichloroethane – $C_2H_3Cl_3$), methyl bromide (CH_3Br) carbon tetrachloride (CCl_4) associated with supplying inputs into the manufacturing process? Yes/No/Don't Know

Are there any associated emissions of these gases? Yes/No/Don't Know

If yes, please identify the gases and the nature, source and scale of any emissions (in kg of the gas concerned/kg of input material):

Input Material	Ozone-Depleting Gas	Nature, Source and Scale of Emissions

B7 Hazardous Substances Inputs and Releases to the Environment

Are any of the substances in Appendix B used in the supply of inputs to the manufacturing process? Yes/No/Don't Know

If yes, please indicate which substances and the manner of their use (eg used in processing, incorporated in product, emitted from processing etc):

Input Material	Hazardous Substance	Manner of Use

In the course of supplying your inputs are any of the substances in Appendix B released to or deposited in:

(i) air
(ii) surface water bodies
(iii) aquifers
(iv) sewer
(v) landfill
(vi) storage facilities?
Yes/No/Don't Know

Questionnaire Appendix A

<u>Greenhouse gases</u>

Direct greenhouse gases

Methane (CH_4)

Nitrous oxide (N_2O)

Hydrofluorocarbons (HCFCs)

Perfluorocarbons (PFCs)

Sulfur hexafluoride (SF_6)

Indirect greenhouse gases

Carbon monoxide (CO)

Oxides of nitrogen (NO_x)

Non-methane volatile organic compounds (NMVOCs)

Appendix B: NPI-listed Substances for the Reporting Year 2001-2002 Onwards

Acetaldehyde
Acetic Acid (ethanoic acid)
Acetone
Acetonitrile
Acrylamide
Acrylic Acid
Acrylonitrile (2-propenitrile)
Ammonia (total – NH_3 + NH_4^+)
Aniline (benzenamine)
Antimony and compounds
Arsenic and compounds
Benzene
Benzene hexachloro- (HCB)
Beryllium and compounds
Biphenyl (1,1-biphenyl)
Boron and compounds
Butadiene (vinyl ethylene)
Cadmium and compounds
Carbon disulfide
Carbon monoxide
Chlorine
Chlorine dioxide
Chloroethane (ethyl chloride)
Chloroform (trichloromethane)
Chlorophenols (di, tri, tetra)
Chromium (III) compounds
Chromium (VI) compounds
Cobalt and compounds
Copper and compounds
Cumene (1-methylethylbenzene)
Cyanide (inorganic) compounds
Cyclohexane
Dibromomethane
Ethanol
Ethoxyethanol
Ethoxyethanol acetate
Ethyl acetate
Ethyl butyl ketone
Ethylbenzene
Ethylene glycol (1,2-ethanediol)
Ethylene oxide
Di-(2-ethylhexyl) phthalate (DEHP)
Fluoride compounds
Formaldehyde (methyl aldehyde)
Glutaraldehyde
n-Hexane
Hydrochloric acid
Hydrogen sulfide
Lead and compounds
Magnesium oxide fume
Manganese and compounds
Mercury and compounds
Methanol
Methoxyethanol
Methoxy ethanol acetate
Methyl ethyl ketone
Methyl methacrylate
Methylene*bis*(pheylisocyanate)
Nickel and compounds
Nickel carbonyl
Nickel disulfide
Nitric acid
Organo-tin compounds
Oxides of nitrogen
Particulate matter 10μm (PM_{10})
Phenol
Phosphoric Acid
Polychlorinated dioxins and furans (PCDDs & PCDFs)
Polycyclic aromatic hydrocarbons (PAHs)
Selenium and compounds
Styrene (ethylbenzene)
Sulfur dioxide

1,1,2,2-Tetrachloroethane
Tetrachloroethylene
Toluene (methybenzene)
Toluene-2,4,-diisocyanate
Total nitrogen (giving rise to nitrate/nitrite ions only)
Total phosphorus (amount giving rise to phosphate ions only)
Total volatile organic compounds (VOCs)
Trichloroethane
Trichloroethylene
Vinyl chloride monomer
Xylenes (individual and mixed isomers)
Zinc and compounds

APPENDIX B

Environmental Performance Questionnaire

For manufacturers and distributors of building materials, products, systems and services.

DETAILS OF MANUFACTURER AND PRODUCT:

Manufacturer Details:

Company Name:

Street Address:	Postal Address:	Phone:	Manufacturing Site Street Address:
City/Town:	City/Town:	Fax:	City/Town:
Country:	Country:	Web:	Country:

Product Information:

Function(s):	Brand:	Product:

Respondent's Details:

Contact Name:	Position:	Phone:
Fax:	Email:	

Please note that if you have any queries regarding this questionnaire or need some assistance, please do not hesitate to contact Gaya (gayag@formway.com). Some sections may be difficult to fill in so please supply as much information as possible.

Overview

Please indicate the major input materials that you obtain and how they are processed to make the product you supply Formway Furniture (i.e. a brief description of your manufacturing methodology).

Minor materials do not need to be included unless they are likely to be of particular environmental significance.

(If you are aware of the efficiency of your processes, please indicate the respective efficiency, and also indicate the approximate proportion of raw materials for product)

Input Material (eg. Aluminium, nylon etc)	How the material is processed into the product you provide Formway	Efficiency (%)

Are any of your input materials from a recycled or reused source? Yes/No/ Don't know

Please indicate the material and its respective recycled content

Input Material (eg. Aluminium, nylon etc)	Recycled content (%)

What are the major wastes produced during your manufacturing process and how are they dealt with?

(Give quantities per kg of product where possible)

Do you have specific cleaner production/pollution prevention initiatives implemented? (Give a brief description of what they are)

Please indicate how your products are transported to Formway, together with the respective distances

Product	Road (km)	Rail (km)	Sea (km)	Air (km)

APPENDIX C

As awareness of the sustainability concept grows, more and more organizations are striving to adapt sustainability principles. Many use techniques such as environmental assessment, risk assessment, sustainability assessment, etc. to help plan for mitigation actions as well as to assess their progress in terms of sustainable development. In relation to the traditional concept of sustainable development, the most accepted definition from "Our Common Future", more popularly known as the Bruntland Commission, is as follows:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:
>
> - The concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and
> - The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."
>
> (WCED, 1987, p. 43)

While this definition has been adopted by industry, putting the concept to operation has been tedious at best. However, if we consider the sustainability of a system (e.g. a production system), from the WCED definition it is clear that two objectives must be met to ensure the sustainability of that system:

1. To provide for the needs of the system; and
2. To ensure the continuation of the system by allowing the supply of those needs to be met.

From these two objectives it can be argued that once the needs to the system have been identified, the risks to the supply of those needs should be addressed in order to achieve the second objective: continuation of the system. Previous LCA work done highlights the significant needs of a production system (i.e. inventory of inputs to manufacture Life, Free, Grid, etc.). What remains to be done includes the identification of risk and the development of a strategy to address risk to ensure the continued supply of those needs to the production system.

These discussions were aimed at determining if the above strategy correlates with what management sees as risk to business and how they relate to sustainability of the organization.

1) Define what is meant by 'risk'

2) When considering short, medium and long term risks, what kind of time period are we talking about?

3) What do you consider are the main short term risks to Formway?

4) What do you consider are the main medium term risks to Formway?

5) What do you consider are the main long risks to Formway?

6) Risk factors that may affect a business include:
    a. Health issues
    b. Legal issues
    c. Environmental issues
    d. Social issues
    e. Economic issues

   What is likely to affect the on-going operations of Formway?

7) How is Formway dealing with these risks?

Short
Medium
Long

8) Do you think there is a link between sustainability and risk? What do you think it might be?

9) Do you see sustainability as a risk or opportunity?

10) In terms of sustainability, where would you like Formway to be?
