Universiteit Utrecht

Faculty of Geosciences

MSc in Sustainable Development
(Energy & Resources)

Master Thesis
(GEO4-2321)

'Towards a Methodology for the Sustainability Assessment of Technologies'

Integration of Environmental, Social and Economic Indicators

Luis Janeiro
L.A.Janeiroramos@students.uu.nl
3320901

Supervision:
Dr. Martin Patel
Prof. Dr. Kornelis Blok

April 2011

Acknowledgements

I would like first to express all my gratitude to Dr. Martin Patel, not only for his very valuable scientific inputs, but also for his inexhaustible generosity and patience during the whole process of this research. He managed to turn every meeting throughout this project into an uplifting milestone, and helped me far beyond his responsibilities as an academic supervisor when I went through tough personal circumstances.

I would also like to remember some of the people I have met during the course of this master. All of them have had a great positive impact on my life. I have to give special thanks to: Katrin Heer, Tabaré Arroyo, Arno van Den Bos, Benjamin Cok, Erik Klaassen, Luli Pesqueira, Pablo López, Giovanni Simoni, Marie Halbach, Wouter Ernst, Laia Fayet, Sara Herreras, Benyam D. Mezmur, Marcelo Ribeiro and María Parra. All we have lived together, and all that I have learnt from you, is certainly the most valuable reward from this master.

Finally, I could have never completed this adventure without the permanent and unconditional support of my beloved family: Mamá, Papá, Pili, Toño, Isi, Candeliña and Santiaguiño.

Thanks to all of you.

Abstract

The development of new technologies has always been a key factor for human progress. Technologies allow humans to provide greater levels of social and economic welfare while using natural resources more efficiently, but they also increase our capacity to inflict greater impacts on the environment. Therefore, technologies play a central role not only for social and economic development, but also for environmental sustainability. For this reason, the availability of methodologies and tools to perform integrated assessments of the sustainability of technologies – including environmental, economic and social indicators – is of the utmost importance in order to steer society along a sustainable pathway.

The aim of this research is to analyze the possible underlying rationales – as well as the available methodologies – for the integration of environmental, economic, and social indicators into sustainability assessments of technologies.

The first step of this research discusses the pros and cons of two existing initiatives of integrated sustainability assessments (PROSA and CALCAS). Secondly, a conceptual framework is proposed. This conceptual framework shows the main systems involved in the ideal of *sustainable development*, as well as the enabling role that technologies play in the interaction between those systems. The third research step discusses different concepts of sustainability, with the purpose of analyzing the extent to which a sustainability assessment can be supported in objective scientific facts, i.e. to distinguish the normative and descriptive parts in the ideal of *sustainable development*. Special attention is given to the debate between the *weak and strong sustainability* paradigms, concluding that there is a sound scientific case for the *strong sustainability* paradigm to support the assessments. Furthermore, it is also concluded that it is possible in principle to put this paradigm into practice by defining environmental thresholds supported on the concept of critical natural capital. The fourth research step analyzes different methodologies for the integration of indicators, including valuation methods and multi-criteria approaches. Besides, the implications of an integrative process are analyzed. The conclusions of the fourth research step are: firstly, that an integrative assessment of sustainability does not require an aggregation of the assessments on each of the dimensions into a single-score index of sustainability. Secondly, that in order to put the *strong sustainability* paradigm into practice by considering environmental thresholds, non-compensatory multi-criteria approaches will have to be used at some point of the process.

Finally, considering the previous conclusions, a proposal for an integration framework is put forward in the last section of this report.

Keywords: sustainability assessment, indicators, critical natural capital, technologies, multi-criteria analysis, weak and strong sustainability, life-cycle assessment

List of Acronyms

Acronym	Definition
AD	Accumulated Damage
AHP	Analytic Hierarchic Process
BAU	Business as Usual
CALCAS	Coordination Action for innovation in Life-Cycle Analysis for Sustainability
CBA	Cost-Benefit Analysis
CNC	Critical Natural Capital
DTT	Distance To Target
EU	European Union
GDP	Gross Domestic Product
GHG	Green House Gasses
IISD	International Institute for Sustainable Development
ISEW	Index of Sustainable Economic Welfare
IUCN	International Union for the Conservation of Nature
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MCA	Multi-Criteria Assessment
MCDM	Multi-Criteria Decision Making
NREU	Non Renewable Energy Use
PROSA	Product Sustainability Assessment (www.prosa.org)
R&D	Research and Development
RQ	Research Question
SAT	Sustainability Assessment of Technologies
SD	Sustainable Development
SLCA	Social Life Cycle Analysis
UNCSD	United Nations Commission for Sustainable Development
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development
WPM	Weighted Product Model
WSM	Weighted Sum Model

Table of Contents

1 Introduction 8
1.1 Problem Definition 9
1.2 Aim of this Master Thesis 9
2 Research Background 10
2.1 Definition of 'Technology' 10
2.2 Definition of Sustainability Indicators 10
2.3 Definition of a Sustainability Framework 10
3 Research Questions 11
4 Methodology 12
4.1 General Methodology 12
4.2 Methodological Steps 12
5 Research Step I: Review of Existing Sustainability Assessment Methodologies 13
5.1 General Review 13
5.2 PROSA (Product Sustainability Assessment) 14
5.2.1 LCA under PROSA. The EcoGrade interpretation framework 15
5.2.2 Life cycle costing and eco-efficiency 15
5.2.3 Social life-cycle assessment in PROSA 15
5.2.4 The 'ProfitS' integrated evaluation framework 16
5.2.5 Discussion on the Method 16
5.3 The CALCAS Project 18
5.3.1 Overview of the project 18
5.3.2 Normative Positions: Sustainability Paradigms in CALCAS 19
5.3.3 Dimensions of Sustainability in CALCAS 21
5.3.4 Aggregation of results and decision-making under CALCAS 21
5.3.5 Discussion on CALCAS 22
5.4 PROSA – CALCAS Comparative 22
6 Research Step II: Definition of a Conceptual Framework 23
6.1 Justification and Aim 23
6.2 Conceptual Framework for Integrated Assessments: A Proposal 24
7 Research Step III: Analysis of Sustainability Paradigms 27
7.1 Analysis of Concepts of Sustainability from Literature 27
7.1.1 Sustainability as an Ethical Paradox 28
7.1.2 Sustainability as Preservation of Capital: Weak vs. Strong Sustainability 29
7.1.3 Sustainability as Equity 30

7.2 In Pursuit of an Integrated and Comprehensive Sustainability paradigm 32
7.3 The Optimal 'Strength' of the Supporting Sustainability Paradigm..............................34
7.4 The Case for a 'Red Line' Defining 'Non-negotiable' Environmental Assets...............37
8 Research Step IV: Integrative Sustainability Assessment Methodologies 39
8.1 An Overview of Decision-Making Tools for Integrative Assessments 39
8.1.1 Monetary Valuation Methods and Cost-Benefit Analysis 39
8.1.2 Multi-Criteria Decision Making (MCDM) 41
8.2 Implications of an Integrative Sustainability Assessment 44
8.3 Integration of Critical Natural Capital in the Sustainability Assessment 48
9 Conclusions & Discussion 53
9.1 Recommendations..55
10 Integration of Sustainability Indicators: A Proposal...56
11 References...58
12 List of Tables 63
13 List of Figures 64
14 List of Equations 65
15 Appendices...66
15.1 Social Indicators for SLCA in PROSA...66

1 Introduction

The progress of the human race has been driven to a great extent by the discovery, development, and diffusion of new technologies. From early breakthroughs such as the discovery of fire or the invention of the wheel, up to the era of supersonic air travel, nuclear power, or the extensive access to the internet, new technologies bear witness to the successful human endeavour. New technologies create new opportunities for human progress while increasing the capacity of humans to create new and greater impacts on the environment. They unveil new paths to increase social welfare, but they usually come hand by hand with new environmental, economic or societal challenges.

Technologies play a central role in the sustainability of the environmental, economic and social systems. The aggregated environmental impact of the global economy can be expressed as a function[1] of population, consumption per capita, and environmental impact per unit of consumption. (Commoner, 1972). The last of these three factors is directly influenced by the state of technology. Therefore, *ceteris paribus* (population and consumption per capita) technology is the dominant factor of environmental sustainability. But the influence of technologies is not restricted to the environmental system. Technologies also shape the societal systems dramatically. The availability of certain basic technologies such as sanitation or electricity is key to achieve minimum levels of social and economic development. Furthermore, different technological alternatives have differentiated impacts on the societal system e.g. creation of employment and economic wealth, working conditions, safety, etc. throughout the life cycle of the product or service provided.

In the last couple of decades, societies have progressively embraced the ideal of sustainable development as the cornerstone of social, economic and environmental policies. In this context, sustainability assessment has been introduced as a new scientific discipline that aims to inform all actors of society (individual citizens, NGO's, governments, corporations) in order to steer society towards that goal. Methodologies to assess different aspects of sustainability at product level (traditional LCA, different initiatives of eco-labelling, etc.), at corporate level (Global Reporting Initiative, Sustainability Index, etc.) or even at societal level (Genuine Progress Indicator, Green GDP, ecological footprint, etc.) are already in place or in implementation stages (Singh, Murty, Gupta, & Dikshit, 2009). Some of these initiatives e.g. PROSA[2], CALCAS[3], address the issue of analyzing the environmental, social and economic dimensions into integrated assessments. However, a widely accepted methodology to perform integrated sustainability assessments at the level of technologies is still missing.

Given the central role of technological progress in the quest for sustainability, society will require tools to identify which technologies perform best in this pursuit. Therefore, defining appropriate methodologies to perform integrated sustainability assessments at the level of technologies is a key element in order to design future policies that are in line with the ideal of *sustainable development*.

---

[1] This has been traditionally known as the IPAT equation: Impact = Population x Affluence x Technology. Source: Chertow, M. R. (2001). The IPAT Equation and Its Variants. Changing Views of Technology and Environmental Impact. *Journal of Industrial Ecology , 4* (4), 13-29.

[2] Product Sustainability Assessment (www.prosa.org)

[3] Coordination Action for innovation in Life-Cycle Analysis for Sustainability.

1.1 Problem Definition

Most definitions present the idea of *sustainable development* as a three dimensional concept where environmental, social and economic aspects have to be taken into account. Each of these dimensions is the result of the composition of several different factors. For instance, energy consumption, land use or chemical pollution are some of the heterogeneous aspects that must be taken into account in order to assess the environmental sustainability of any human activity. The assessment of the social and the economic dimensions require similar compositions of heterogeneous measures. Besides, these three dimensions of sustainability are not only heterogeneous but also dependent upon each other. Societal welfare depends on environmental factors such as clean air and water, resource availability and many others. It is also apparent how social welfare relies on the performance of the economy. Conversely, any successful economy runs on social and environmental resources.

As a result of all these heterogeneities and dependencies, assessing the sustainability of a certain human activity, technology, or product becomes an extremely complex task to address. Multi-criteria assessment has been extensively used as a tool to assist decision-making in the context of this kind of complex analyses, e.g. (Buchholz, Rametsteiner, Volk, & Luzadis, 2009) (Mendoza & Prabhub, 2000). The application of multi-criteria methodologies involves an aggregation process including the selection of indicators as well as normalization and weighting procedures. These inevitably introduce subjectivity into the decision-making process.
Subjectivity arises at least in two forms: Firstly, there is no definitive agreement on the content of the concept of sustainable development itself. There are different legitimate ways to look at this ideal – discussed in section 7.1 – that result in implicit assumptions about what has to be considered in a sustainability assessment. Secondly, subjectivity also arises when assigning relative importance to the different aspects that have been considered in the sustainability assessment.

In light of these undeniable sources of subjectivity, it is even more important to devise coherent objective methodologies in order to assist the sustainability assessment process. These methodologies have to provide the structure to make subjective choices explicit, in order to guarantee the general quality and comparability of the assessments.

1.2 Aim of this Master Thesis

The aim of this project is to study the process conducing from a set of indicators on the environmental, economic and social performance of technologies into an integrated sustainability assessment.

The different concepts of sustainability, influencing the choice of indicators as well as their relative weight in the decision-making process, will be analyzed. Besides, different ways of approaching the weighting process will be considered: different MCA (multi-criteria assessment) methods will be analyzed, dissecting the pros and cons of the available options within the MCA scope and proposing objective methodologies for their application that guarantees the quality, comparability and objectivity of these assessments.

2 Research Background

2.1 Definition of 'Technology'

For the purpose of this project *technology* will be defined as any set of techniques, methodologies or tools built on accumulated scientific knowledge – and typically using energy and/or materials from nature – that are used to deliver a certain service or product – functional unit – to society.

2.2 Definition of Sustainability Indicators

The definition of a set of sustainability indicators is intimately connected with the process of defining what is meant by sustainable development and what should be monitored in order to lead our society towards that goal. Boulanger (2008) defines indicators as 'observable variables used to report non-observable realities'. For the purpose of this project, a sustainability indicator is any measurable parameter – quantitative or qualitative – that can inform the sustainability assessment of the technologies under analysis, aiding the decision-making processes in order to design appropriate policies.

2.3 Definition of a Sustainability Framework

The most widespread and accepted definition of *sustainable development* is *'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (UN WCED, 1987). While this definition might have been successful enough to trigger social and political action in the years after the publication of the report, it is still too vague to be operationalized. Thus, *sustainable development* remains nowadays a contestable concept that leads to a wide range of possible interpretations in practice.

The term *sustainability*[1] has been historically used – and still frequently is – as a more restricted concept than *sustainable development.* It is intimately connected with the idea of intergenerational equity through the preservation of the environment or 'ability to sustain' (Manderson, 2006), usually leaving aside subjective social constructs around the questions of what exactly constitutes human development. In this sense, *sustainability* may be understood as a synonym of *environmental sustainability*. Still, different concepts of *sustainability* understood in a broader sense have been devised from different perspectives and scientific fields with the intention to boil these definitions down to a certain set of meaningful and objective indicators or operational principles. See: (Parris & Kates, 2003) (Hueting & Reijnders, 1998) (Renn, Jäger, Deuschle, & Weimer-Jehle, 2009) (Pearce D. , 1988) (Jabareen, 2008) (Daly H. E., 1990)

Given this wide range of possible interpretations, the first obstacle to be overcome when confronted with the task of assessing the *sustainability* of a certain technology is to define under which definition of the term this assessment will be made. If a specific, objective and measurable conceptual framework for *sustainability* is not appropriately defined, the assessment can be performed in as much detail as it might be technically possible, but it risks to be flawed at the very top. In order to make any kind of meaningful measurement of *sustainability* it is therefore imperative to establish the boundaries of what can be defined in a purely *objective* manner within the set of features that the concept of *sustainable development* embodies. The choice of a certain *sustainability paradigm* clearly affects the two main points of any assessment process, namely:

[1] The term 'sustainability' is commonly used in different scientific disciplines to describe states or conditions that can be maintained indefinitely. For further information about the historical roots of the concept of sustainable development see: Du Pisani, J. A. (2006). Sustainable development - Historical roots of the concept. (Taylor&Francis, Ed.) *Journal of Integrative Environmental Sciences , 3* (2), 83-96.

1. The ***choice of the set of indicators*** to be measured. Those indicators that will inform the decision-making process.
2. The ***relevancy (relative weight), priority, and/or hierarchic position*** that is assigned to each of the indicators during the decision-making process.

3 Research Questions

Two research questions have been defined. They point at bridging the knowledge gaps described in section 1.1: The first research question addresses the very foundations of any sustainability assessment, namely, the paradigm under which that assessment will be done, as well as the limits of scientific knowledge in defining this paradigm when confronted with conflicting but legitimate value systems. The second research question addresses the various possibilities for the interpretation of those indicators into integrated assessments.

These are the two research questions addressed in this master thesis:

RQ1*: Is it possible to build a sound scientific case for a particular sustainability paradigm as a basis to support the sustainability assessment of technologies?*

RQ2: *What is the most appropriate methodology for the integration of indicators across the various dimensions of sustainable development?*

4 Methodology

4.1 General Methodology

The research methodology is based on the theoretical analysis of available literature on sustainability assessment frameworks, sustainability indicators and indices, as well as methodologies for the integration of indicators and decision-making.

4.2 Methodological Steps

The research methodology is divided into four steps (see Fig. 4.1):

The first step consists of a review of existing sustainability assessment methodologies, focusing on those where parallelisms can be established with our particular case of technologies.

In the second step, a conceptual framework for the analysis of integrated sustainability assessments is put forward.

The third step comprises the review and analysis of the different perspectives on the concept of sustainable development available throughout the scientific literature. This analysis implies a discussion on the implications of the choice of a particular paradigm to support sustainability assessments. Furthermore, it analyzes the extent to which is it possible to build a strong scientific case for a particular paradigm (RQ1).

Finally, the fourth step consists of the evaluation of different methodologies to compile the results from the different domains/dimensions of sustainability (usually: environmental, economic, social) into integrated assessments of sustainability (RQ2).

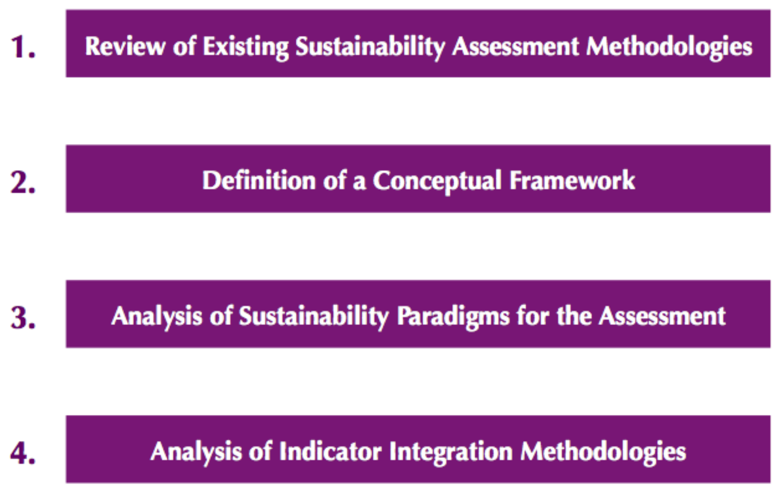


Fig. 4.1: Research methodology – methodological steps

5 Research Step I: Review of Existing Sustainability Assessment Methodologies

5.1 General Review

The interest in developing indicators to evaluate the different aspects of sustainable development has been increasing in the last couple of decades. As a matter of example, the International Institute for Sustainable Development (IISD) keeps a compendium[1] of 'sustainability indicators initiatives', including over 600 initiatives at global, national, regional and local level. Singh et.al (2009) provides a recent overview of some of the most relevant initiatives of sustainability indicators and indices that are already common practice for policy-making. Among these are development indices, market and economy-based indices, ecosystem based indices, etc (Singh, Murty, Gupta, & Dikshit, 2009). Although there are an increasing number of initiatives to measure sustainability, Singh et.al concluded that only a few of them have an integral approach taking into account environmental, economic and social aspects.

<u>Life cycle thinking, required to assess the sustainability of technologies:</u>

The environmental impact of any technology spreads out along every stage of its life cycle, from the extraction of the raw materials, to the use stage, up until the final disposal of waste back to the environment. The same applies for the economic and social impacts associated with the use of the technology. For this reason, when assessing the performance of technologies across the three areas of sustainability (social, environmental, economic) an analysis along all the stages of the life cycle is required. LCA (life cycle assessment) is a well-established methodology that has been in use for several years to assess and compare the environmental impact of products. Furthermore, the comprehensive scope of LCA is useful 'in order to avoid problem shifting, for example, from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another' (Finnveden_et.al, 2009). A similar approach, based on the definition of comparable *functional units,* can be taken for the integrated sustainability assessment of technologies.

However, LCA focuses primarily in the environmental dimension of sustainability. New methodologies need to be developed in order to cover the performance of technologies at the economic and social level. Some methodologies have been developed to assess the economic costs of products with a 'cradle to grave' perspective (life-cycle costing or LCC). Kloepffer (2008) points out that LCC is a useful complement to LCA, as an indicator of the potential success of the product in the market. However, LCC is not enough to measure the whole economic dimension. It fails to capture the macroeconomic effects, e.g. the contribution to GDP growth resulting from the use of the technology under analysis. Similarly, it does not capture the intangible economic values such as the accumulation of technological knowledge itself.

Similarly, relevant work is being done in the field of social life-cycle assessment (SLCA) (Benoît_et.al, 2010). This relatively new line of research within LCA has several challenges ahead, among which are how to decide which are the relevant indicators, the quantification of the impacts, and how to relate quantitatively the values of the indicators to the functional unit (Jørgensen, 2008).

Following the widely accepted 'three pillar' view of sustainability, Kloepffer, (2008) proposes two possible options to integrate the results of LCC and SLCA into a life-cycle sustainability assessment: The first option is to perform three separate life cycle assessments with the same system boundaries. No compensation between the three pillars is allowed; therefore, no aggregation across the three dimensions should be performed:

[1] For further information, see www.iisd.org/measure/compendium

$$LCSA = LCA + LCC + SLCA$$

Eq. 5.1 Life-cycle sustainability assessment of products

According to Kloepffer, the best advantage of this approach is its transparency. Results are comparable and information is not lost in the aggregation process.
The second option is to create a completely 'new' LCA, where LCC and SLCA are integrated as new impact categories.

Given the focus of this thesis on the sustainability at the level of technologies I have selected for further analysis two initiatives that are comparable in terms of purpose and scope. Both initiatives take a life-cycle approach. Furthermore, both aim at providing an integrated assessment consider environmental, economic and social aspects. In the following points these two initiatives will be described and critically analyzed:

5.2 PROSA[1] (Product Sustainability Assessment)

PROSA is a methodology for the strategic analysis and evaluation of product portfolios, products and services. It was developed by the Öko-Institut for Applied Ecology in Germany, and its primary focus is on corporate product development as well as strategic product portfolio planning. It spans along the complete life cycle of end products, including the analysis of the whole value chain to produce them. The methodology pays particular attention to the analysis of social and economic issues, as well as to the consideration of utility aspects and consumer research. The goal of this methodology is to identify system innovations and options for action towards sustainable development (Institute for Applied Ecology, 2007). Among the possible practical applications of the PROSA methodology, are:

- Strategic planning and product portfolio analysis in companies.
- Product policy and dialogue processes.
- Sustainable consumption and product evaluation.
- Product development and marketing.

PROSA can also be used to analyse sustainability at other levels, such as technologies, large infrastructural projects or geographical units (Institute for Applied Ecology, 2007).

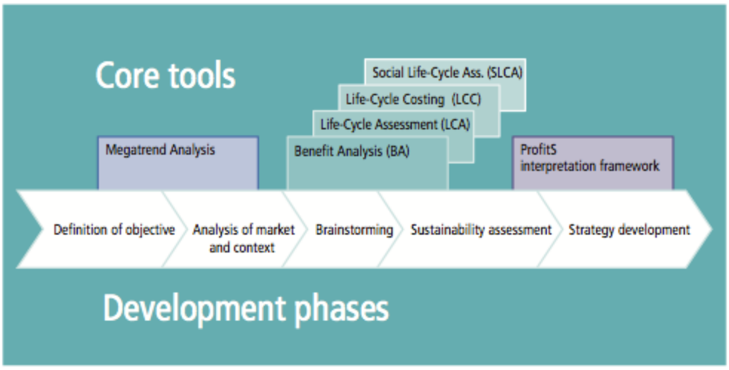


Fig. 5.1 Overview of PROSA's sequence of work. Source: www.prosa.org

The methodology starts with a product portfolio analysis. The aim of this analysis is to identify the areas, business units, or key products to be analyzed in more depth. It includes a traditional market-oriented portfolio analysis complemented by an analysis of social and environmental aspects of sustainability. Once the key elements of the product portfolio are identified, PROSA proceeds with the sustainability assessment stage. For that purpose, it incorporates existing tools

[1] For further information, see www.prosa.org

and methodologies such as traditional LCA conforming to the ISO Standards 14040 / 14044. It also includes LCC (Life-Cycle Costing) and SLCA (Social Life-Cycle Assessment) modules, which follow the same methodological steps – goal and scope definition, inventory analysis, impact assessment, and interpretation – as traditional LCA. The last step of the PROSA methodology is assisted by a set of ad-hoc interpretation frameworks that integrate the results from the previous modules, assisting the development of sustainability strategies.

5.2.1 LCA under PROSA. The EcoGrade interpretation framework

PROSA considers several LCA impact categories of resource consumption (e.g. energy carriers, minerals, or water) and environmental impact (e.g. greenhouse gases, acidification, eutrophication etc.) and reports them in relation to a defined functional unit. A differentiating characteristic of PROSA is the aggregation process. ISO standards 14040/14044 explicitly prohibit aggregation of results across impact categories when comparative results are to be disclosed to the public, because, it is a *'value-laden process that can be hardly based on scientific evidence'* (Finkbeiner_et.al, 2006). However, PROSA identifies aggregated environmental indicators as *'particularly necessary when considering several or many products, and specially so when economic and social aspects are included'* (Institute for Applied Ecology, 2007). For this reason, the methodology includes an external interpretation framework – referred to as EcoGrade, which aggregates the results from the different impact categories. The aggregation process is based on weighting factors derived from 'socially agreed quantitative environmental targets[1]', and expressed in environmental target impact points (Umwelt -Ziel-Belastungs-Punkt – UZBP). According to this methodology, the environmental target impact points of the individual impact categories are added without any further weighting – it is assumed that all environmental targets agreed by societal consensus or legislative statute have equal weight (Institute for Applied Ecology, 2007). Impact categories for which no quantitative environmental targets have yet been formulated are integrated within the overall result by means of a set percentage weighting. (Institute for Applied Ecology, 2007). However, no further information could be found in literature as to which is the scientific rationale to define these weighting factors, nor scientific arguments to support them.

5.2.2 Life cycle costing and eco-efficiency

PROSA carries out a life-cycle costing assessment (LCC) of the product under analysis. LCC is performed following similar steps as a traditional LCA – scope definition, inventory analysis, cost assessment, and interpretation. The availability of the information on life-cycle costs coupled with the (aggregated) environmental results from the previous stage (traditional environmental LCA) enables a two-dimensional analysis of the results, the so-called 'eco-efficiency' assessment. The term eco-efficiency was first coined in 1992 by the Business Council for Sustainable Development in its report 'Changing Course' (WBCSD, 1996). In the context of product sustainability assessment, eco-efficiency refers to the ratio of economic creation to ecological destruction (Saling_et.al, 2003). PROSA understands eco-efficiency analysis as a *'tool for comparative assessments of environmental and economic aspects – and indeed in general wherever social aspects do not play a major role or data on such aspects are difficult to collect'*. The difference between a simple a cost-effectiveness analysis on energy efficiency or CO_2 emissions and an eco-efficiency analysis is that the eco-efficiency considers the aggregated results of the environmental assessment (Institute for Applied Ecology, 2007).

5.2.3 Social life-cycle assessment in PROSA

The social aspects of the product are considered by means of a social life-cycle assessment. According to the Öko-Institut – the developer of the PROSA methodology - the goal of this

[1] We will refer to this methodology or similar approaches as 'distance-to-target' later in the text

evaluation *'is not to arrive at an absolute evaluation of particular products, but to derive possible measures for improving social problems'* (Institute for Applied Ecology, 2007). PROSA distinguishes four categories of indicators[1]: employees, local and regional communities, society, and users & consumers. The social assessment is carried out by means of the 'SocioGrade' interpretation framework, a 'semi-quantitative' method which is operationalized in an excel spreadsheet model. In this model, indicators across the four categories can be freely chosen and evaluated. Evaluation takes place in a 1 to 10 scale, from 1 – 'high': social situation very good, to 10 – 'low': social situation very poor. The excel model sets a 1:1 weighting factor for each indicator that is considered in the analysis, although these weighting factors can be modified by the user. (Institute for Applied Ecology, 2007).

5.2.4 The 'ProfitS' integrated evaluation framework

PROSA includes a final interpretation framework in which the results of the environmental, economic, and social assessment are analyzed in an integrated fashion. For this purpose, the average results across the three dimensions (between 1 = very good, and 10 = very poor) are plotted in a bar graph or a spider diagram. According to the Öko Institute, the PROSA excel tool provides an aggregated single-score evaluation of sustainability for the product by means of a 1:1:1 weighting process across dimensions.

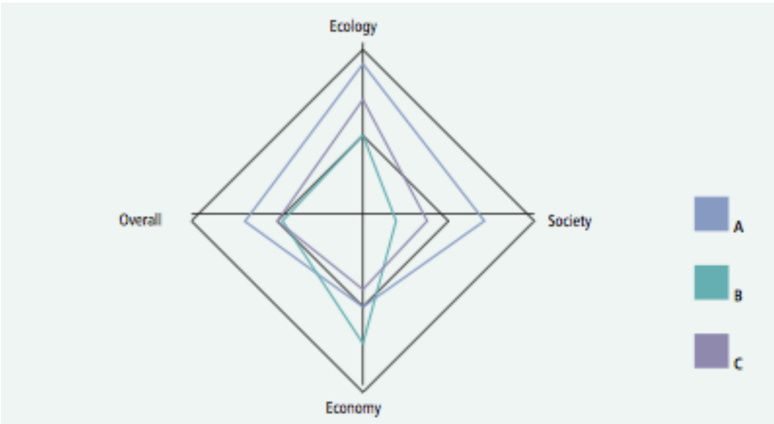


Fig. 5.2: Spider graph for Integrated Sustainability Assessment of three product alternatives under PROSA (Institute for Applied Ecology, 2007)

5.2.5 Discussion on the Method

PROSA is a praiseworthy attempt to define a structured market-oriented methodology in order to perform integrated sustainability assessments of products, including not only the economic dimension, but also environmental, and social considerations.

A distinctive and interesting feature of PROSA is the inclusion of an analysis of the product's 'utility'. This utility is defined at different levels (practical utility, symbolic utility, and societal utility). PROSA refers to this as 'Benefit Analysis'. The definition and analysis of societal utility implies a definition of certain products or forms of consumption as 'intrinsically sustainable' or 'intrinsically unsustainable'. According to PROSA's webpage: *'the state should intervene when the ecological or societal burdens of products are too high for the common good'* (Institute for Applied Ecology, 2007). As true as this claim might possibly be, it requires further definitions of what is 'too high' and what is 'the common good' i.e. to explicitly define what is the particular view of sustainable development that informs this decision (see section 2.3).

---

[1] The complete list of indicators can be found in appendix 15.1

The environmental assessment of products under PROSA follows the methodological lines of a traditional LCA as is defined in the ISO standards 14040/14044. However, PROSA goes one step further[1], using the results from this analysis to perform a normalization and aggregation process in order to arrive to a single-score environmental indicator. The process to arrive to the weighting factors required for the aggregation process is based on 'socially agreed environmental targets'. This, however, does not say anything about how environmentally critical or scientifically sound they are. Furthermore, no explanation could be found as to how the weighting factors are obtained in those cases where no 'socially agreed targets' have been defined.

It is undoubtedly true that the cost of the product defines to a certain extent the economic efficiency of the process to provide the buyer/consumer – and by extension, to society as a whole – with a defined utility. Low costs help to ensure social access to certain products or utilities (although in this last sense, costs could arguably be as well considered as a social sustainability indicator, rather than an economic one). However, low costs are not necessarily always good. On the one hand, low energy and resources costs increase the incentive for consumption, therefore increasing the aggregated environmental impact of the economy. On the other hand, low costs may also have a negative short-term effect on employment, as companies tend to move their investments to products with high margins of profit. In any case, the analysis of the life-cycle costs of the product gives us very little insight on the macroeconomic effects, i.e. the accumulated economic wealth derived from the consumption of certain products. Thus, the analysis of the product's life-cycle costs does not give a complete view of the economic dimension.

Although the stated goal of PROSA is not to provide a detailed 'diagnosis' of the social aspects of a particular product, its 'SocioGrade' framework tries to operationalize social assessments and integrate them into product evaluations. Nonetheless, this process is still fraught with methodological difficulties[2] and sources of subjectivity. The fact that the assessment framework leaves it up to the user to choose the relevant indicators is a clear source of arbitrariness to the analysis. Furthermore, the evaluation of each specific indicator in a 1 to 10 scale is highly subjective when it is not accompanied by objective guidelines. Finally, there is no explicit rationale backing the choice of 1:1 weighting factors.

Regarding the last integration process, the ProfitS interpretation framework has similar weaknesses as those shown by its input modules. It is difficult to evaluate the scientific soundness of the normalization and aggregation processes from the information available on the methodology. Likewise, there is no explicit scientific rationale to attribute 1:1:1 weighting factors – or any other – to each of the three identified dimensions of sustainability (environmental, social, economic).

In sum, PROSA's methodology is far from being a fully convincing and operational tool. However, it constitutes a relevant step forward in the field of product evaluation in order to structure the process leading to the product's sustainability assessment.

---

[1] ISO standards 14040/14044 explicitly prohibit aggregation of results across impact categories when comparative results are to be disclosed to the public.

[2] Data gathering requirements are often very extensive, making it very difficult to track down social aspects of upstream processes / subcomponents leading to the final product.

5.3 The CALCAS[1] Project

5.3.1 Overview of the project

CALCAS was a EU 6th Framework Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability, aimed at expanding the boundaries of traditional ISO-LCA. The starting assumption of the CALCAS project is that life cycle assessment, as standardised by ISO, is the most suitable method for the environmental analysis of products, but it requires a broadening of scope and a deepening of modelling practices in order to address more complex sustainability issues. The general objective of CALCAS was to develop ISO-LCA by:

- "Deepening" the present models and tools to improve their applicability in different contexts while increasing their reliability and usability.
- "Broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance.
- "Leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation (Heijungs_et.al, 2010).

In other words, the purpose of the CALCAS project is to analyze the available options, knowledge gaps, and research needs in order to transform traditional environmental LCA into a broader tool for sustainability assessments with a life-cycle perspective. The prime focus of CALCAS is on the environmental pillar, with due consideration to the economic and – to a lesser extent – the social dimension of sustainability (Heijungs, Huppes, & Guinée, 2009). One of the outputs of the CALCAS project is a blue paper where a proposal for a system approach for life-cycle sustainability analysis (LCSA) is put forward (Zamagni, et al., 2009). According to Zamagni et.al, 2009, CALCAS proposes 'a single unitary framework for LCSA, as "logical" structure able to incorporate knowledge from all domains relevant to sustainable development and to identify a coherent way to link micro analysis (where it is possible to implement a very detailed model, as ISO LCA does) to the macro level where, indeed, most questions of sustainability reside'.

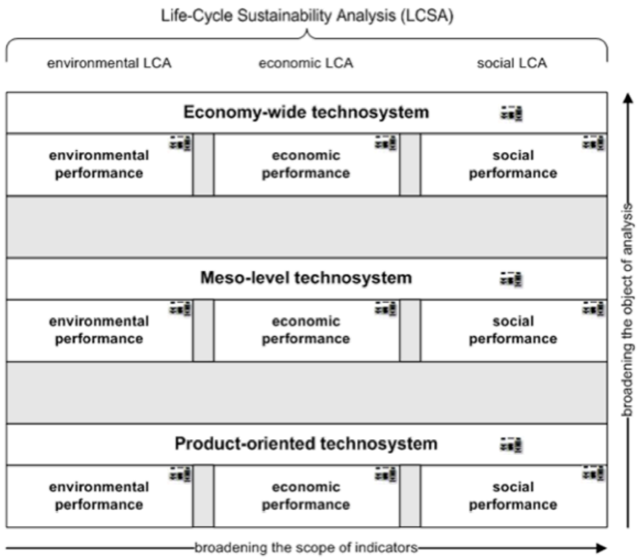


Fig. 5.3: LCSA framework proposed by CALCAS. Source: (Guinée, Huppes, Heijungs, & van der Voet, 2009)

Fig. 5.3 shows the unitary framework for LCSA proposed in CALCAS. Three levels of analysis are defined: product-level, meso-level and economy-wide.

[1] For further information: www.calcasproject.net

5.3.2 Normative Positions: Sustainability Paradigms in CALCAS

CALCAS does not embrace a particular sustainability paradigm with regards to key issues such as the substitutability of natural capital, the concept of equity, or the 'appropriate' relative weight of the different indicators in the sustainability assessment. Instead, it acknowledges the existence of different legitimate views on the idea of sustainable development. According to Heijungs et.al (2009) the suggestion that scientific analysis can give a complete answer to questions such as the sustainability of projects, technologies, etc. is only partially true, due to the following reasons:

> • 'An answer to questions on sustainability requires normative elements, such as trade-offs between economy and environment and aspects of intergenerational equity;
> • A sustainability analysis involves self-denying prophecies, e.g. in predicting undesired consequences, which will be combated before they have the chance to develop;
> • Even the aspects that are factually true are in many cases badly known to the scientists, because they involve complex and novel phenomena'.

CALCAS concludes that a scientifically based sustainability analysis necessarily involves value judgments, assumptions, scenarios and uncertainties. Once this is acknowledged, the aim is *'not so much to decrease the non-factual content of a SA, nor to hide it, but to explicitly incorporate it by adding elements such as uncertainty analyses and discursive procedures'* (Heijungs, Huppes, & Guinée, 2009).

CALCAS understands the normative analysis as of an entirely different nature from empirical analysis, as it is not about knowledge of what *is*, but about normative positions of what *ought to be*. For this reason, CALCAS makes a distinction between sustainability as a 'positive' science – describing it as a property of the systems that is to be measured and analyzed, and sustainability as a 'normative' science (Heijungs, Huppes, & Guinée, 2009). This is reflected in the new framework for LCSA proposed by CALCAS, where normative positions complement empirical knowledge at the modelling stage[1] (see Fig. 5.4).

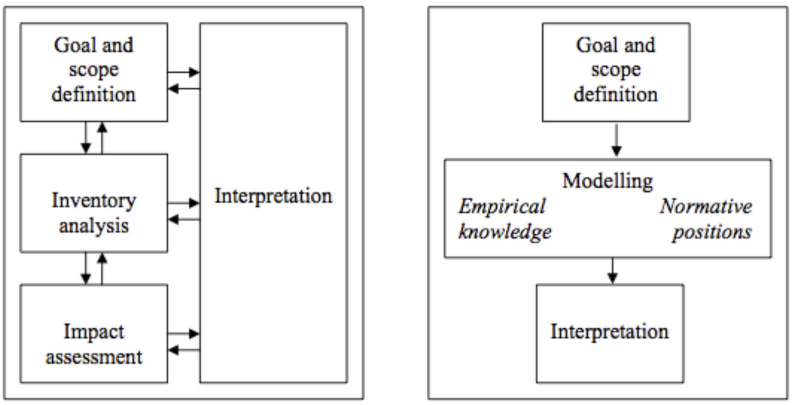


Fig. 5.4: Left: ISO-LCA framework. Right: New LCSA framework proposed by CALCAS. Source: (Zamagni, et al., 2009)

However, the case studies analyzed during the course of the CALCAS project showed how the distinction between normative and empirical domains *'is only a way to manage the complexity of the system, because actually a sharp separation is not possible, due to the strong*

[1] The new framework, compared to the ISO one, includes few but significant differences, in particular with the merging of inventory and impact assessment in just one modelling step Zamagni, A., Buttol, P., Buonamici, R., Masoni, P., Guinée, J., Huppes, G., et al. (2009). *Life Cycle Sustainability Analysis.* Coordination Action for Innovation in Life Cycle Analysis for Sustainability. CALCAS.

interrelations' (Heijungs, Huppes, & Guinée, 2009). CALCAS acknowledges the difficulty of incorporating socio-cultural, institutional and political models into the modelling stage of the new LCA framework, suggesting that they could be taken into account via stakeholder involvement in the goal and scope definition and interpretation stages. Fig. 5.5 shows the conceptual separation of the domains of empirical knowledge and the domains of normative positions, including a subdivision of the components of those domains:

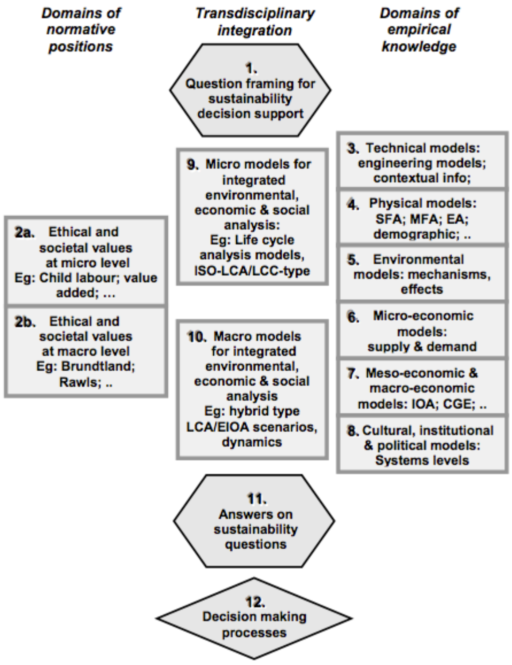


Fig. 5.5: Separation of empirical knowledge, normative positions and transdisciplinary integration. Source: (Zamagni, et al., 2009)

The CALCAS project sets a research agenda in which *'options for ethical positions and societal values in LCSA'* are to be evaluated. This agenda has, among others, the following expected results:

• *''A view on how different indicators might be combined, either as a lexicographical ordering (first criterion 1 to be satisfied; only then taking nr 2 into account; etc.) versus different weighting procedures, within environmental effect domains and between different domains of sustainability.*

• *An operational set of weighting factors covering the domains of sustainability, conditionally linked to different ethical positions in the sustainability debate''* (Guinée, Huppes, Heijungs, & van der Voet, 2009).

5.3.3 Dimensions of Sustainability in CALCAS

CALCAS takes the traditional view of sustainable development as a three-dimensional concept (environment, economy, society). It expands the scope of traditional LCA, restricted to the environmental pillar alone by a wider one, in which all three 'pillars' are covered (Zamagni, et al., 2009). Following the rationale that has been discussed in section 0, no specific weighting factor or predominant hierarchic position is given to any of the three domains of sustainability, leaving it open to different – legitimate – ethical positions.

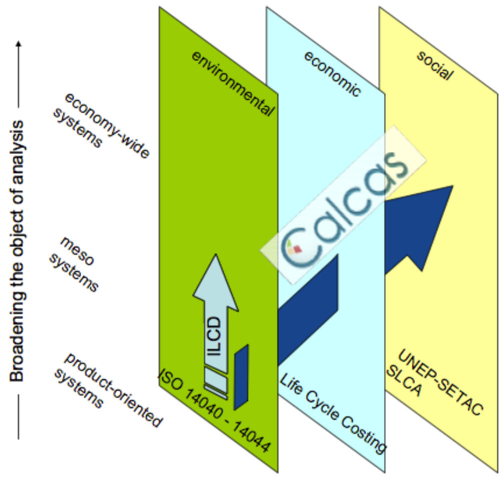


Fig. 5.6: CALCAS conceptual framework for broadening the scope of ISO-LCA. Source: (Zamagni, et al., 2009)

5.3.4 Aggregation of results and decision-making under CALCAS

By expanding traditional ISO-LCA into LCSA, a higher number of indicators will be taken into account, including social and economic domains. There is a potential need for aggregation of results within these new domains, as well as across the three domains, in order to aid the decision-making process. CALCAS considers two possibilities for the aggregation of results and decision-making in LCSA:

- Multi-criteria analysis techniques (MCA)
- Valuation methods.

Multi-criteria techniques considered for LCSA include weighting procedures as well as so-called outranking methods. Valuation techniques are a way of aggregation in which external costs are evaluated in monetary terms. Valuation techniques considered in CALCAS include willingness to pay, damage costs, hedonic pricing and revealed reference (Heijungs, Huppes, & Guinée, 2009).

5.3.5 Discussion on CALCAS

As opposed to PROSA, CALCAS is not a methodology for sustainability assessments, but a thorough research agenda in order to transform current environmental LCA methodologies into integrated LCSA (life cycle sustainability assessment).

CALCAS identifies normative components of the concept of sustainable development, distinguishing them from empirical knowledge in the new LCSA framework (see Fig. 5.4). In this regard, CALCAS approach is not to take a stand embracing a particular paradigm, but rather, to acknowledge that different legitimate normative judgements exist and that those should be made explicit in the analysis. However, very little information could be found in the project documentation as to how to operationalize these normative positions in sustainability assessments in practice, only suggesting that weighting factors might be derived using panel discussions, interviews, policy documents or monetary principles (Heijungs, Huppes, & Guinée, 2009).

CALCAS takes the traditional view of sustainable development as a three-dimensional concept (environment, economy, society). CALCAS also identifies a potential need for aggregation of results coming from the different domains of sustainability in order to assist the decision-making process. Two sets of tools are considered for this purpose: Multi-criteria analysis and valuation methods. However, these integrative methodologies are only identified, but not developed in further detail. Moreover, CALCAS does not discuss specific rationales for the integration of indicators, i.e. the underlying assumptions behind the allocation of weights or hierarchical positions of those indicators.

5.4 PROSA – CALCAS Comparative

The following table compares the main features of the two discussed methodologies:

	PROSA	CALCAS
Use orientation	Market oriented - Products	Science Oriented – Products, Technologies, Services
Definition of sustainability paradigm	Implicit	None
Dimensions/domains of sustainability considered	Three-dimensional + Utility	Three-dimensional
Choice of indicators	-	According to LCA standards
Focus	None	Environmental Pillar
Levels of Analysis	Product Level	Product level, meso level, economy wide
Integration/aggregation of results	Aggregation to single score	MCA / Valuation methods (Identified but not developed)

Table 5.1: PROSA-CALCAS comparison. Source: own elaboration.

6 Research Step II: Definition of a Conceptual Framework

6.1 Justification and Aim

The conventional way of looking at sustainable development presents it as a three dimensional concept composed by the environmental, social, and economic components. A common way to refer to these three components or pillars - especially in the corporate sphere - is as Planet, People, Profit or 'triple bottom line'.

Fig. 6.1 Left: Traditional three-dimensional view of SD. Right: (Heijungs_et.al, 2010)

According to this paradigm, the assessment of Sustainable Development is the result function of the individual assessments along these three independent components. This assumption, however, is hardly rooted in empirical evidence or physical reality. In fact, it is easy to observe that the social systems and the economic production associated to them are fully contained within – and hence fully dependent on – the global environmental system. Furthermore, it is easy to observe that the social, economic and environmental systems are not only interconnected but also closely interdependent upon each other. Economic production depends on the availability of natural resources as well as human capital. In a similar fashion, social development cannot be disassociated from the level of income and it is also fully dependent on a healthy environment. Therefore, I will argue that these components of sustainable development (environmental, economic, social) cannot be simply considered as three linearly independent variables. For this reason, the first step in order to perform a sustainability assessment is to identify the fundamental systems and processes underlying the concept of sustainable development as well as their main interdependencies. These systems and interactions can arguably be mapped in a conceptual framework that is rooted in physical reality, enabling meaningful debate in order to propose appropriate sustainability indicators as well as rationales for their integration.

Herman E. Daly referred to this – citing Josef Schumpeter – as a need for a shared '*pre-analytic vision*'. He argued that whenever we engage in analysis we do not start from scratch. We start from a certain perception of the nature of the object under analysis (the concept of sustainability and the systems involved, in our case) and this perception determines to a great extent the conclusions of the analysis (Daly H. E., 1997).

Providing a conceptual framework of sustainability assists in the important task of bringing these normative assumptions to the surface, making them explicit in order to move the debate forward, and design appropriate policies based on our best scientific knowledge. Thus, the aim of this chapter is to put forward a proposal for an integrated conceptual framework with a focus on the sustainability assessment of technologies.

6.2 Conceptual Framework for Integrated Assessments: A Proposal

As it was mentioned earlier, the aim of a conceptual framework is to provide a common basis to structure the debate on the sustainability of technologies. For this reason, it is important to define rigorously which is the debate that we are addressing. Two possibilities arise:

1. The debate on how 'sustainable' it is for a society to consume certain *functional units* in particular, i.e. the sustainability of the action per se, in absolute terms.
2. The debate on how 'sustainable' it is to provide the same *functional unit* using a certain technology in comparison with other available options, i.e. the sustainability of a particular technology in relative terms.

The first of these two debates relates to the absolute impact of an activity as compared with a defined – local, regional, global – carrying capacity. Some methodologies have been devised in order to perform these kinds of analyses e.g. the ecological footprint (Rees, 1992) (Wackernagel M. , 1994). However, this debate addresses a purely normative question. Modern democracies protect the freedom of individuals to choose between alternative forms of consumption. The sustainability of a certain functional unit per se, e.g. *1 km·person of road transportation*, as compared with the consumption of alternative functional units e.g. *1 kg of meat*, *1 kg of rice,* or *1 hour of cellular phone call* can only be assessed in subjective terms. In other words, it is a political task to steer society in order to prioritize and allocate the 'available carrying capacity' into alternative forms of consumption. For this reason, this question falls outside the scope of this thesis.

The second debate, on the other hand, can be addressed on more objective grounds. It is possible in principle to compare the performance of alternative technologies – all providing the same functional unit – in different impact categories e.g. resource consumption, employment, income distribution, etc. It is true, however, that normative decisions inevitably arise when deciding about the relative weight of each of the impact categories in the overall sustainability assessment. It is at this point when a conceptual framework is required, with the following three main purposes:

1. To function as a shared tool that structures the debate in order to derive a meaningful set of sustainability indicators for technologies, as well as to provide the rationales for their integration.
2. To analyze the role that technologies play and the place that they occupy in the interaction between the relevant systems, namely the environmental and the socio-economic systems.
3. To visualize in a simplified model the nature of the interactions and hierarchic relations between environment, society, and economy.

Fig. 6.2 shows a graphic interpretation of the proposed conceptual framework displaying the systems involved in the sustainability assessment: the environmental system (green), the societal system (blue), and the socio-economic system (red). It also reflects which forms of capital are associated to each of them: natural capital, social capital and human-made capital, respectively. Finally, it represents the physical interactions between the systems with a LCA approach (orange arrows).

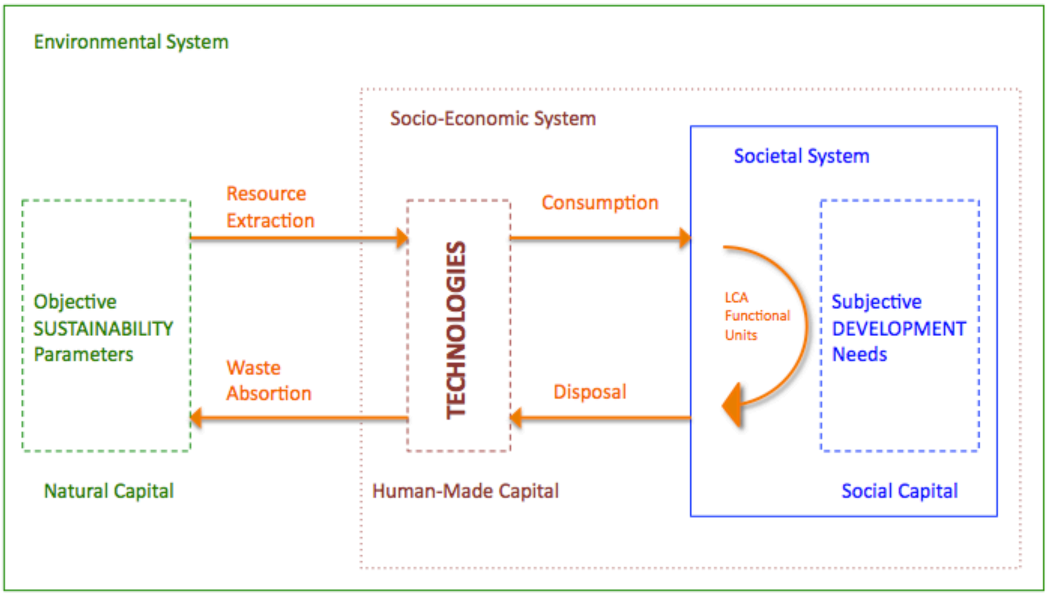


Fig. 6.2: Proposed conceptual framework for the sustainability assessment of technologies

<u>Description of the systems involved</u>

The societal system (represented in blue) is considered a dependent subsystem of the natural environment under the proposed framework. It represents the aggregation of individual human beings. Human development needs are the driving force behind the consumption of goods and services – life cycle functional units – that keeps the economy running, thus enabling the accumulation of human-made capital. At least two sources of subjectivity arise within the societal system: Firstly, human needs have a strong subjective component. Once basic (objective) needs, such as access to food and shelter are met, different people will give different answers to the questions: What do you need and/or how much do you need to lead a successful life? This affects the definition of what exactly is social sustainability. Secondly, the perception of the environment – the value that people assign to nature – is also different across societies and individuals. This affects the definition of environmental sustainability.

The socio-economic system is conceptualized as an expansion of the societal system. In other words, it represents human societies – societal system – plus the tools and any other form of accumulated economic capital associated to the human activity (buildings, roads, factories, energy plants, etc…). The economic capital accumulated around human societies can also interpreted as the sphere of interaction between the societal and the environmental systems. It is through the use of these tools that humans can increasingly transform the inputs from the environmental system to fulfil their needs. If we consider early human societies, the socio-economic system could almost be assimilated to the societal system, as the number of human-made capacities and accumulated capital were very limited. In our time, particularly after the industrial revolution, the 'size' of this human-made expansion of the societal system is continuously growing – economic growth – arguably leaving in the process ever less room for the environmental system to provide the required inputs – as well as to absorb the associated outputs. This phenomenon of economic expansion is at the root of the sustainability challenge that lies ahead.

The environmental system represents planet Earth as a whole, including the atmosphere, hydrosphere, lithosphere and ecosphere. In other words the environmental system encompasses every form of natural capital.

The role of technologies under this framework

Technologies can be conceptualized as a form of accumulated human-made capital within the socio-economic system. They are at the core of the physical interaction between the societal system and the environmental system (see Fig. 6.2). Technological state-of-the-art determines the environmental and societal impacts throughout all the stages of the life cycle associated with the consumption of a functional unit within the societal system. Better technologies are able to provide the same functional unit with a smaller physical impact on the environment i.e. requiring less resource extraction and producing smaller amounts of waste. Similarly, better technologies are able to provide the same functional unit with a better societal impact, e.g. enabling better working conditions or creating more wealth – measured as contribution to GDP – per unit consumed.

Sustainability is ultimately a property of the environmental and the societal systems. Technologies are human-made capacities to be used by society: *'The key link between the socio-economic domain and our physical surroundings lies in the technosphere. There, affluence is created by combining natural resources and human ingenuity, mostly at an environmental cost. Technology is the link, not the aim'* (Guinée, Huppes, Heijungs, & van der Voet, 2009). As such, technologies are not the ultimate concern of sustainability, but means to achieve it. This is reflected in Fig. 6.2, technologies are conceptualized as an interface between environment and society. For this reason, technologies can hardly be assessed as intrinsically sustainable or unsustainable. Instead the sustainability of a technology has to be assessed in terms of its potential contribution and its impacts on the sustainability of the environmental and societal system.

Description of the interactions between systems

The map shows the tension between subjective human development needs and objective (although usually uncertain) environmental sustainability parameters defining the state of the natural capital. The balance between both represents the paradox underlying the concept of sustainable development. Technologies are at the core of this tension enabling the societal system to meet increasing needs, at the expense of an impact (negative or positive) on the different forms of natural capital. The map shows the interactions between the relevant systems with a 'cradle to grave' life cycle approach. It considers all the stages required for a certain technology to provide a given *functional unit* to the societal system.

7 Research Step III: Analysis of Sustainability Paradigms

7.1 Analysis of Concepts of Sustainability from Literature

In order to have an overall view of the historical interpretations of sustainability across different disciplines, a literature review has been made. Jabareen (2008) provides a comprehensive critical review of multidisciplinary literature on sustainable development. The result of this review is a list of seven different concepts or meanings of sustainability:

Different ways of understanding *Sustainability*	
Concept	*Application*
Ethical Paradox	**Environmental protection vs. human development**
Natural Capital Stock	**Strong sustainability vs. weak sustainability**
Equity	**Intergenerational and intragenerational equity**
Eco-Form	Ecological design of human habitats
Integrative Management	Bring together all stakeholders for decision-making
Utopianism	Utopian view of a perfect society where justice prevails, people are perfectly content, flourishing in harmony with nature.
Political Global Agenda	Globalization of the environmental discourse

Table 7.1: Different concepts of sustainability (Jabareen, 2008)

He goes on to propose a conceptual framework including all the identified concepts of sustainability around the central idea of the ethical paradox between environmental protection and human development. According to Jabareen, this conceptual framework shows the different levels at which the concept of sustainable development operates, as well as an overall view of how the concept has been approached from different scientific disciplines. While this framework might be relevant from a theoretical point of view, it does not bring any further insight on how to operationalize the concept in order to assess the sustainability of technologies or assist political decision-making.

The first three concepts (*ethical paradox, natural capital stock, equity*) reflect three alternative ways of approaching the idea of sustainable development from different disciplinary traditions; When considered together, they cover the main actors and aspirations in the idea of sustainable development as it has been presented historically, i.e. the stability of the environmental system, the progress of the human endeavour, and the equal distribution of opportunities within generations as well as from one generation to another. These three concepts will be discussed in more detail below and overlaps or redundancies between them will also be analyzed.
The last four concepts identified by Jabareen lack the sense of completeness of the former three. The concept of *eco-form* is limited to the design of human habitats. The concepts of *integrative management* and *political global agenda* do not address the description of what sustainability is but only proposed ways of steering society towards it. Finally, the utopian view is of very little practical use, as it requires making unrealistic assumptions about social behaviour in order to define sustainable futures. We will therefore focus the analysis on the first three of these concepts in our search for supporting pillars to build an integrated conceptual framework of sustainability.

7.1.1 Sustainability as an Ethical Paradox

The term 'Sustainable Development' is a paradoxical composition of two apparently irreconcilable concepts. On the one hand, a restricted definition of sustainability points at a state in which a certain characteristic of a system – in particular the environmental system – can be preserved indefinitely. On the other hand, the term development represents human progress, which has been to this day associated with an increasing human use of land, energy and resources, resulting in an expansion of the human systems having an impact on the environmental system. There is a continuum of different ethical approaches to this paradox, from extremist anthropocentric positions up to extreme ecocentric 'deep ecology' views.

Anthropocentric		**Ecocentric**	
Extreme 'Cornucopian'	Accommodating	Communalist	Deep Ecology
Resource exploitative-growth orientated position	Resource conservationist and managerial position	Resource preservationist position	Extreme preservationist position
Instrumental value in nature	Instrumental value in nature	Instrumental and intrinsic value in nature	Intrinsic value in nature

Table 7.2: Anthropocentric vs. ecocentric worldviews. Based on: (Pearce & Turner, 1990)

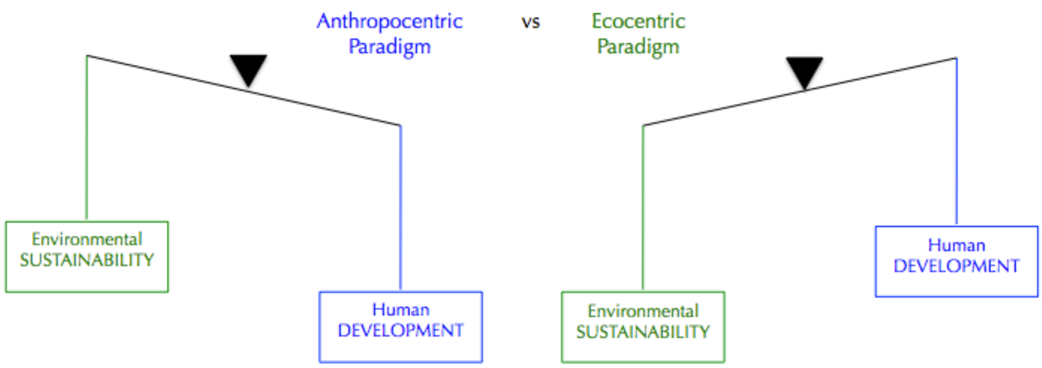


Fig. 7.1: The paradoxical balance underlying the concept of sustainable development

Any sustainable future lies somewhere in between this continuum. The exact point where this equilibrium is optimal will depend on a number of factors such us global population, level of income (proxies to global consumption and environmental impact) and the state of technology (better technologies allow higher levels of consumption keeping the environmental burden at comparable levels). This shows that the state of technology plays a central role in the equilibrium along this ethical paradox, and it should be reflected in any meaningful conceptual framework of sustainability. The global level of consumption, together with the state of technology, can serve as objective factors defining where the world is in this continuum at a given moment. However, deciding how far we may go in this tension between human development and environmental sustainability – how much strain we allow ourselves to put on the environment – remains a value-laden decision. The choice of a certain set of sustainability indicators is affected by this ethical decision.

However, the concept of *carrying capacity* can be helpful in order to determine acceptable levels of human impact on the ecosystems. Rockstrom et.al (2009) defined a list of safe 'planetary boundaries' that could inform the choice of indicators for this purpose.

7.1.2 Sustainability as Preservation of Capital: Weak vs. Strong Sustainability

When the concept of Sustainable Development is approached from a merely economic perspective, it can be defined in terms of a comparison between the present and future capacity to create welfare. The idea behind the concept of capital is that it is a stock that possesses the capacity of giving rise to flows of goods and/or services (Ekins, Simon, Deutsch, Folke, & Groot, 2003). According to this view, Sustainable Development can be defined as '*development that does not decrease the capacity to provide non-declining per capita utility for infinity'* (Neumayer, 2003). The capacity to produce utility[1] is directly dependent on the stock of capital, being it in the form of available natural resources, as 'manufactured' (human-made) capital or in the non-material forms of capital e.g. accumulated knowledge. When the concept of sustainability is analyzed as an evaluation of the stock of different forms of capital over time, two opposing paradigms arise, namely *weak sustainability* and *strong sustainability.* These two paradigms are discussed in more detail in section 0.

Natural Capital

Goodland (1995) defines environmental sustainability as the *'maintenance of natural capital'*. According to him, natural capital can be defined as *the stock of environmentally provided assets, which provide a flow of useful goods and services*. Accordingly, environmental sustainability should be operationalized as a set of constraints on the activities of the human economic subsystem in order to preserve the natural capital. Common & Stagl, 2005 divide the services provided by natural capital to the socio-economic system into four categories, namely: Life-support services, resource base, waste sink, and amenities (Common & Stagl, 2005). Some authors have undertaken the task of valuing natural capital and its services (Constanza_et.al, 1997). Indicators pointing at these services should be included in any set of sustainability indicators in order to provide a picture of the state of depreciation of natural capital.

Human, Social and Human-Made Capital

Accordingly, economic sustainability and social sustainability can be defined as maintenance – or increase – of their respective capital stock. Common and Stagl, (2005), define economic capital stock as the sum of *durable capital* (machinery, infrastructures, etc.) *human capital* (stock of learned skills), *intellectual capital* (accumulated knowledge) and *social capital* (set of institutions that organise economic activity). Goodland, (1995) defines social sustainability in terms of preservation of *'moral capital',* achieved *'only by systematic community participation and a strong civil society'*.

System	Capital	Form of Capital	Source
Environmental Sustainability	Natural Capital	Life-Supporting Services Resource Base Waste Sink Amenities	(Common & Stagl, 2005) (Ekins, Simon, Deutsch, Folke, & Groot, 2003)
Economic Sustainability	Human-made Capital	Durable Capital Human Capital Intellectual Capital Institutional Capital[2]	(Common & Stagl, 2005)
Social Sustainability	'Moral' Capital	Cohesion and community Cultural Identity Diversity Solidarity Tolerance, etc.	(Goodland, 1995)

Table 7.3: Different forms of capital stock.

[1] The terms 'utility' and 'welfare' are used indistinctly in this work, following the same criterion of Neumayer, E. (2003). *Weak versus Strong Sustainability: Exploring the limits of two opposing paradigms.*

[2] We use the term 'institutional capital' in order to avoid confusion with the social or moral capital that is matter of social sustainability.

7.1.3 Sustainability as Equity[1]

The view of sustainability as equity highlights the human dimension of the concept, introducing certain qualitative and normative requirements for the term development. The Rio Declaration on Environment and Development highlighted the human dimension of sustainable development in its first principle: '*Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature'* Principle five goes further to include eradication of poverty and the reduction in disparities of standards of living as a central part of sustainable development (UNCED, 1992).

The ideas of intergenerational and intragenerational equity have been present around the concept of sustainable development from its very conception. The requirement of intergenerational equity can be easily identified in the most widespread definition of the concept: *'Development that meets the needs of the present without compromising the ability of the future generations to meet their own needs'*. The concern about intragenerational equity is also made explicit in the following terms in the Brundtland report: *'…even the narrow notion of physical sustainability implies a concern for social equity between generations, a concern that must logically be extended to equity within each generation…'* (UN WCED, 1987). As this excerpt from the Brundtland report suggests, the requirement of intragenerational equity is a logical and unavoidable consequence of the concern for future generations. Jahnke & Nutzinger, 2003 expressed this same logic in the following way: *'The link between inter- and intragenerational fairness is inevitable both from an ethical – philosophical and from a practical perspective: from the viewpoint of ethics, there is an immediate maxim that people who feel responsible for the well-being of their descendants should feel at least just as responsible for the well-being of their contemporaries. Viewed from a practical perspective, problems of intragenerational distribution obviously cannot be resolved as long as there is no way of resolving the present environmental problems: if there is no sufficient acknowledgement of present and immediately following generations' interests, the request for general intergenerational fairness is beyond any chance of realization'* (Jahnke & Nutzinger, 2003).

Obviously, the concept of equity or justice comprises a wide range of possible interpretations (e.g. utilitarianism, libertarianism, etc…). Gosseries, (2005) discusses six different ways of looking at intergenerational justice concluding that distinct operational principles can be derived from them (see Table 7.4).

TABLE: Theories of intergenerational justice – a synoptic table.

	(positive) savings[a]	dissavings[b]
indirect reciprocity	authorised	prohibited
collective property	authorised	prohibited
utilitarianism	obligatory	prohibited
Rawlsian egalitarianism		
▪ **phase 1**	obligatory	prohibited
▪ **phase 2**	authorised	prohibited
luck egalitarianism		
▪ **phase 1**	obligatory	prohibited
▪ **phase 2**	prohibited unless …	prohibited unless …
Brundtland's sufficientarianism	authorised unless …	authorised unless …

a (Positive) savings: Each generation transfers more to the next one than what it inherited from the previous one.
b Dissavings: Each generation transfers less to the next one than what it inherited from the previous one.

Table 7.4: Theories of intergenerational justice and operating principles (Gosseries, 2005)

[1] The term equity is used in a broad sense in this paper, reflecting the equality of different individuals and generations in the access to all forms of capital, not only economic capital. Equity is used as a synonym of justice in this context.

He points out that Brundtland's *'suffientarian[1]'* approach to sustainable development fails to meet two principles expressed in egalitarian theories such as Rawls' *Theory of Justice* (Rawls, 1999), and his own proposed 'luck egalitarian' view of intergenerational justice. Firstly, Brundtland's view allows intergenerational *dissavings,* as far as we ensure that there is enough for the next generation to provide for their own (basic) needs. However, such dissavings would be violate the egalitarian principles. Secondly, Brundtland's perspective also allows for intergenerational savings as long as it does not jeopardize the ability of the current generation to meet its own needs. Gosseries argues that this is also an unfair operational principle for the least well off of the present generation.

Gosseries' analysis illustrates how Brundtland's particular view of justice, although widely cited and publicly accepted, is only one out of many legitimate views, and therefore it is not scientifically incontestable. In a similar fashion, other theories of justice such as utilitarianism or libertarianism have also to face equally legitimate critiques.

In conclusion, it is undeniable that the concept of sustainable development contains equity requirements, both between and within generations of humans. However, there is to this day no commonly agreed way of materializing these equity requirements into scientifically incontestable operational principles. In other words, the desirable reach of the idea of equity or justice, as well as its practical implementation, still belongs to the realm of politics.

[1] According to Gosseries, a view in which once basic needs are covered, no further redistribution is required.

7.2 In Pursuit of an Integrated and Comprehensive Sustainability paradigm

The previous sections discussed three different ways of looking at the concept of sustainable development. We will now try to understand how these relate to each other and what are the possibilities of finding an integrated and comprehensive paradigm.

As it was discussed earlier, the concept of intergenerational equity is at the roots of the ideal of sustainable development. It provides the ethical justification for the preservation of the different forms of natural capital for future generations. Likewise, it provides the justification for the development and preservation of new forms of human-made (e.g. durable, intellectual, institutional) as well as moral capital[1] (e.g. cohesion, culture, tolerance) to make them available for future generations. The paradigm of sustainability as preservation of capital, however, does not say anything about how the access to all these forms of capital should be distributed within generations (i.e. intragenerational equity). So, in principle, if we only consider the preservation of capital among generations, a sustainable world could still be dramatically unfair. In this sense the idea of sustainable development as intragenerational equity goes further than the mere preservation of capital, expanding the concept of sustainability and bringing new requirements to it. The support for the idea of intragenerational equity as a requirement for sustainable development does not come only from the value systems of most modern societies. As it was shown earlier, it is also a logical consequence of pursuing intergenerational equity, for if we care about the welfare of human beings in the future, we should naturally extend those rights to those human beings living in our time (see section 7.1.3).

On the other hand, the ethical paradox between human development and environmental preservation clearly follows similar lines as the tension between strong and weak sustainability. Both visions pose a similar question: Should we refrain ourselves from some forms of progress to preserve the environment? However, the motivations behind the question diverge: while the approach as an ethical paradox between human development and environmental sustainability places the stress on the existence of intrinsic rights of nature, the paradigm of sustainability as preservation of capital can be supported from a purely anthropocentric worldview (i.e. preserving nature not in defence of its intrinsic rights but for the rights of our children). Therefore the tension between human development and environmental sustainability brings a new normative component to the discussion, namely the extent to which the rights of humans prevail over the – allegedly existing – rights of nature.

We can conclude from all of the above that the content of the concept of sustainable development is still – and possibly will always be – in dispute. It has purely normative components such as the desirable reach of inter- and intragenerational equity, the allocation of intrinsic rights to nature, or the level of risk that societies should bear with regards to the degradation of the environment. These components clearly fall in the realm of politics. However, science can and should play a key role in informing the decision-making processes.

On the other hand, the concept of sustainable development also has an objective core. We can objectively analyze which systems are involved in the concept as well as the relevant interactions and dependencies between them. Furthermore, there are objective truths about the well being of humans within the social systems (e.g. access to minimum levels of food, health care and sanitation, institutional stability and freedom, etc.) that can be supported with strong empirical evidence, regardless of our particular political stance. All these components of the ideal of sustainable development can and should be dealt with within the realm of science.

---

[1] Goodland, R. (1995). The Concept of Environmental Sustainability. *Annual Review of Ecology and Systematics* , *26*, 1-24.

The following section is committed to analyze in further detail the tension between the weak and strong sustainability paradigms. In particular, I will discuss the extent to which it is possible to make a choice between them based on purely scientific arguments.

7.3 The Optimal 'Strength' of the Supporting Sustainability Paradigm

It has been previously noted that the results from any sustainability assessment will look dramatically different depending on the sustainability paradigm – namely weak or strong - underlying the analysis. Therefore, an explicit choice has to be made as to which sustainability paradigm is used in order to make the assessment meaningful, comparable and relevant. But, is it possible to find a right balance somewhere in between the weak and strong sustainability paradigms? And, more importantly, is it possible to support this decision with purely objective and sufficiently strong arguments? When grappling with the concepts of weak and strong sustainability it is easy to establish parallelisms with other ways of approaching the sustainability debate. The tension between weak and strong sustainability closely resembles that between neoclassical and ecological economics. Furthermore, both debates stretch along the same lines of the omnipresent ethical paradox underlying the concept of sustainable development, i.e. the tension between human development and environmental conservation. Indeed, it could be argued that they all are only different faces of the same debate being observed from alternative viewpoints (see also section 7.2.)

	Weak Sustainability	**Strong Sustainability**
Disciplinary tradition	Economics	Natural sciences
Economic approach	Neoclassical economics	Ecological economics
Ethical approach	Anthropocentric	Ecocentric
System focus	Socio-economic system	Environmental system

Table 7.5: Parallelism along different disciplinary approaches

The weak sustainability paradigm is rooted in the neoclassical traditional concept of capital and utility - measured as aggregated income. The strong sustainability paradigm, on the other hand, comes from the tradition of the natural sciences, defining sustainability as preservation of the physical stock of the different forms of natural capital, and consistent with the ecological economics view of a socio-economic system constrained by a finite environment.

Far from being two clearly differentiated and fully operational concepts, the weak and strong paradigms are just the two extreme views that define a continuum of sustainability perspectives. Therefore, the search for a supporting paradigm for the sustainability assessment cannot be simply structured as a choice 'between' the weak and strong views. Instead, the question has to be formulated as a 'how strong' or 'how weak' our particular paradigm should be. Goodland (1995) defines three levels of sustainability:

- *Weak Sustainability*, that is concerned with maintaining the total capital stock intact, without regard to the partitioning of that capital among the four kinds. This would imply that the various kinds of capital are more or less substitutes, at least within the boundaries of current levels of economic activity and resource endowment.
- *Strong Sustainability*, that requires maintaining separate forms of capital, and assumes that natural and human-made capitals are not perfect substitutes.
- *Absurdly Strong Sustainability*, by which we would never deplete anything. Non-renewable resources should not be used at all, and renewable resources should only be harvested at the natural growth rate.

The weak sustainability paradigm, which is rooted in the works of Robert Solow (Solow, 1974) and John Hartwick (Hartwick, 1977)[1], assumes substitutability between human-made capital and natural capital, as long as the aggregated income does not decrease over time. The proponents of the strong sustainability paradigm, on the other hand, have raised questions about the substitutability of natural capital. They stress the need to preserve the stock of natural capital in order to ensure a non-decreasing flow of income for future generations (Constanza & Daly, 1992). According to the weak sustainability perspective, any form of capital – including all forms of natural capital – is 'negotiable' as far as the aggregated income does not decrease.

[1] See: Neumayer, E. (2003). *Weak versus Strong Sustainability: Exploring the limits of two opposing paradigms.*

There are possible trade-offs between economic activity and the quality of the environment according to this view. In turn, if the strong sustainability paradigm prevails, the natural capital becomes 'non-negotiable' and environmental quality is given 'an astronomical, or asymptotically infinite, value with reference to that of aggregate economic activity' (Hediger, 1999).

In light of all the above, it can be concluded that the discussion on the optimum between weak and strong sustainability can be reduced to a debate about the acceptable degree of substitution between human-made and natural capital, i.e. to establish a boundary between the 'negotiable' and the 'non-negotiable' parts of our inherited environment.

Hartwick and Solow's account of intergenerational equity – where the *weak sustainability* paradigm is supported – is based on the assumption that manufactured capital can substitute for depleted non-renewable resources. According to them, an optimal allocation of exhaustible resources among generations can keep aggregated income constant over time (Hartwick, 1977). However, as it was discussed earlier in section 0, the aggregate stock of natural capital comprehends much more than non-renewable resources. The other forms of natural capital, in particular *life-support systems* e.g. climate regulation, the hydrological cycle, etc. as well as the *waste absorption capacity,* also contribute to the aggregated income, providing free goods and services at different stages of the economic process.

It is an intuitively strong premise that the immediate short-term effect of a reduction in the supply of environmental goods and services (related to a decrease in the stock of natural capital) would be that of a reduction in the overall output of the economy. The reason for this is that capital and labour would have to be reallocated to provide the share of lost environmental goods and services e.g. clean air and water, climate regulation, natural absorption of waste and pollution, etc. Kaufmann, (1995) performed a model-based[1] analysis to determine whether these short-term effects of environmental degradation persist in the long run. The conclusion of his analysis is that these effects persists over time, diminishing the capacity of the economy to create wealth. According to him, it is possible to maintain the total output of the economy by substituting (human-made) capital for environmental life-support, however, this comes at the expense of a decrease in welfare: *'The shift between consumption and investment is the hidden cost of substituting capital for a reduction in environmental life support. This dynamic is usually ignored by neoclassical economists when they evaluate the ability of capital to substitute for environmental life support. It is possible to substitute capital for environmental life support and maintain total output. But because there is no source of capital other than the fraction of output saved for investment in previous periods, it is not possible to substitute capital for environmental life support and maintain material well-being'* (Kaufmann, 1995).

Kaufmann admits that, to this day, technological progress has been enough to offset the effects of the last decades of environmental degradation if we measure welfare merely as aggregated consumption. However, being this reflection true, it is also true that there is no sound reason to conclude that this can be sustained in the near future, particularly when the increasing global consumption has to be satisfied with a decreasing amount of natural capital.

Eq. 7.1 Shows the Cobb-Douglas production function as adapted by Kauffman, including a scalar (E) representing the level of environmental life-support.

$$Y = E \cdot A \cdot K^{\alpha} \cdot L^{1-\alpha}$$

[1] The analysis is based on a traditional Cobb-Douglas growth model: $Y = EAK^{\alpha} \cdot L^{1-\alpha}$. Where 'E' represents the level of environmental support while 'A' represents the technological scalar (cp the bigger the scalar, the bigger the economic output) Kaufmann, R. K. (1995). The economic multiplier of environmental life support: can capital substitute for a degraded environment? *Ecological Economics , 12*, 67-79..

Eq. 7.1: Kauffman's production function, where Y: aggregated income; E: environmental life support; A: level of technology (total factor productivity); K: manufactured capital; L: labour; α: output elasticity (assumed constant returns to scale)

An analysis of this production function provides us with a preliminary theoretical criterion of sustainability for prospective technologies. We can conclude that *ceteris paribus,* those technologies having a non-negative effect on the multiplier **E·A** can be considered as sustainable under a *weak sustainability* paradigm (substitution of natural capital allowed) as their net contribution is that of a non-decreasing economic output over time. Under this criterion, decreases in the level of environmental support are offset by improvements in the technological level, rather than by an increase in the rate of capital reinvestment, which would have an effect on welfare. If restrictions to the substitutability of natural capital are included in the analysis, a new criterion has to be considered. The effect of the technologies on the environmental assets **E** has to be non-negative.
These sustainability criteria for the contribution of technologies under the two paradigms are summarized in the table below:

Sustainability Paradigm	Criteria
Weak Sustainability	$\Delta(E\cdot A)\geq 0$
Strong Sustainability	$\Delta(E\cdot A)\geq 0$ $\Delta(E)\geq 0$

Table 7.6: Sustainability criteria for technologies

The *strong sustainability* paradigm seems most appropriate to move forward for at least the two following reasons:

a) It acknowledges the ultimate dependence of the social and economic systems on some forms of natural capital. Since natural capital is required for the production of manufactured (human-made) capital, the latter can never be a complete substitute for the former. Constanza and Daly (1992) provide further argumentation for this in the following terms: *'production is a transformation process in which a flow of natural resource inputs is transformed into a flow of product outputs by means of labour (human capital) and manufactured capital. Natural resources are that which is being transformed into products, manufactured and human capital are what is effecting the transformation. The relationship is overwhelmingly one of complementarity, not substitutability.*

b) It is a more precautionary option in light of the lack of complete knowledge about the behaviour and ultimate resilience of the environmental systems. In this sense, Ekins et. al. (2003) highlighted that the destruction of manufactured capital is very rarely irreversible, whereas irreversibility is common in the consumption of natural capital e.g. extinction of species, climate change, combustion of fossil fuels, etc. Furthermore, the precautionary principle was endorsed by the UN in the Rio Declaration: *'In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or 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).

However, the second criterion for *strong sustainability, i.e.* $\Delta E\geq 0$, if applied strictly to every form of natural capital, would leave very little room for any economic activity. It requires leaving nature in a – virtually – pristine state, including keeping all the non-renewable resources unused. Very few human activities, if any, can be identified having a net positive or neutral impact on the environment such as this. Goodland refers to this extreme paradigm as *'absurdly strong sustainability'* (Goodland, 1995).

On the other hand, Solow (1974) and Hartwick (1977) had showed that there are indeed some possible tradeoffs between natural capital and human-made capital. Therefore, in order to avoid falling in an *absurdly strong* paradigm of sustainability, these trade-offs have to be acknowledged.

An integrated approach is required, where some natural assets can be traded for manufactured capital while others are considered as 'non-negotiable'. This implies defining the domains of influence of the weak and strong paradigms. That is the purpose of the next section.

7.4 The Case for a 'Red Line' Defining 'Non-negotiable' Environmental Assets

Setting the boundaries between 'negotiable' and 'non-negotiable' pieces of natural capital is, in principle, a normative decision. It is not possible to state as a scientific fact which parts of nature are 'negotiable' and which parts are not when diverse human needs and values are at stake. The discrimination of 'negotiable' parts of nature will always depend on the particular set of values of the individuals taking the decision. The controversy around oil production in the Arctic illustrates this tension. When looking at the iced planes of Alaska, some see a sacred natural sanctuary that should remain untouched, while others see a legitimate and potentially enormous source of fossil fuels of little environmental value (McCarthy, Blackman, & Dickerson, 2001). Drilling for oil in the Arctic will certainly produce increased income in the form of oil revenues. In turn, it will have a net negative impact in the stock of natural capital. It will decrease the quality of the local ecosystems due to changes in land use and pollution, it will contribute to the depletion of the fossil resource base, and it will contribute to the saturation of the waste absorption capacity of the atmosphere. There is a non-explicit assumption made by those in favour of drilling for oil in the Arctic that follows a weak sustainability rationale: They assume that the increased income from oil revenues can substitute for the forms of environmental capital that are lost.

Being true that the debate on the 'negotiability' of environmental assets cannot be clinched in a purely scientific way, it is also true that the burden of the proof is not equally distributed along both sides of the debate. When someone asks for capital in the financial markets he or she is asked to guarantee that the borrowed capital will be paid back to the lender. In a similar fashion, when analyzing human depletion of natural capital it should be the responsibility of those supporting the depletion to somehow demonstrate that the future returns on investment will pay back the borrowed capital. Pearce, (1988) offers extensive and strong arguments in favour of giving a predominant position to the natural capital as 'a means and instrument for achieving sustainable development': e.g. resource dependence of the poor, the rate of return to investment in natural capital and the extent of non-substitutability between natural and human-made capital. Furthermore, the argument 'everything is negotiable' conflicts with the mainstream scientific consensus that certain critical services provided by the natural capital e.g. climate regulation, clean air, etc. are irreplaceable (Constanza_et.al, 1997) (Rockstrom_et.al, 2009).

As it was pointed out in section 7.3, there is a need for an explicit definition of the domains of influence of the weak and strong sustainability paradigms. The solid evidence for the non-substitutability of some environmental functions[1] provides scientific justification to draw this line. Ekins et.al (2003) defines 'Critical Natural Capital' (CNC) as natural capital that is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital. Given the undeniable uncertainty about

---

[1] De Groot et.al (2002) defines four categories of environmental functions: Regulation (bio-geochemical cycling, climate, water purification, etc.), Production (harvesting from natural ecosystems, food, raw materials, genetic resources), Habitat (refuge and reproduction habitat to wild plants and animals) , and Information (possibilities for recreation and aesthetic enjoyment, cultural and historical information, artistic and spiritual inspiration, education and scientific research)

which environmental functions are important for human welfare and the detailed mechanisms why they are so, Ekins et.al. proposed to identify as critical any environmental function:

1. which cannot be substituted for, in terms of welfare generation, by any other function, whether environmental or not;
2. the loss of which would be irreversible;
3. the loss of which would risk, or actually entail, 'immoderate losses'

Those stocks of natural capital, which perform these functions, and cannot be substituted by other stocks of environmental or other capital that performs the same functions may be called 'Critical Natural Capital' (Ekins, Simon, Deutsch, Folke, & Groot, 2003). However, the problem starts when we are confronted with the task of singling out those stocks of environmental capital that should be preserved at all cost, for environmental stocks provide several environmental functions simultaneously, and some of these functions are more critical than others. Let us take a forest as an illustrating example: a forest provides life-supporting services (e.g. habitats for species, breathable air), it contributes to the resource base (e.g. biomass energy), it is also a waste sink (e.g. CO_2 absorption capacity), and it is a form of amenity. Furthermore, environmental degradation happens incrementally. Therefore, when chopping down trees in a forest we rarely know which one is the one that will trigger the final irreversible damage.

For the two reasons discussed above, it is extremely complex to define 'non-negotiable' environmental assets. Instead, it is possible to define the 'red line' separating the domains of the weak and strong sustainability paradigms by establishing a set of parameters related to critical environmental functions. Rockstrom et.al, (2009) takes this approach. Instead of defining specific environmental stocks that should be preserved, he defines a set of global environmental boundaries that should not be violated in order to preserve life on earth within safe parameters. This approach can be used to operationalize the concept of strong sustainability around these boundaries. Section 8.3 discusses a methodology to make this operational for sustainability assessments.

8 Research Step IV: Integrative Sustainability Assessment Methodologies

The process leading to the construction of an integrated assessment of sustainability can be defined as a three step methodology: the identification of the various dimensions underlying the concept of sustainable development, the process of aggregating lower dimension indicators in higher level composite indices, and the attribution of weights at various levels of the indicators hierarchy (Boulanger, 2008). The previous sections of this research prepared the field for this process by discussing the main approaches to the concept of sustainable development. The following section discusses possible approaches to incorporate the different aspects of sustainable development into integrated assessments, as well as the possibilities for the allocation of weights. Fig. 8.1 shows a graphical representation of this process:

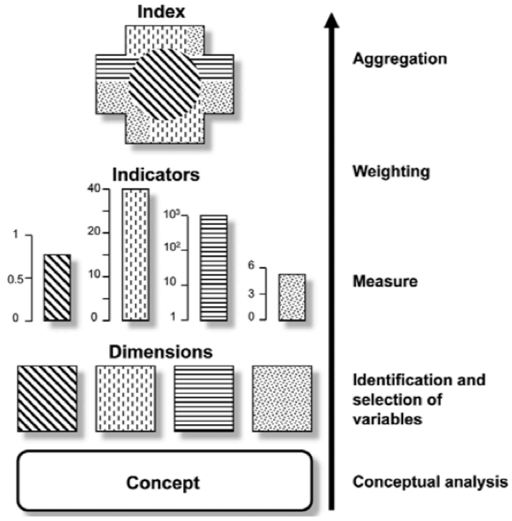


Fig. 8.1: From a concept of sustainability to indicators and indices (Boulanger, 2008)

The discussion starts with an overview of the available tools/methodologies for integrative assessments, including different multicriteria analysis techniques and monetization methodologies (section 8.1). Secondly, I analyze the implications and requirements of an integrative process, including a discussion as to whether an aggregation process is always required when performing an integrative assessment (section 8.2). Thirdly, I analyze the possibilities for aggregation and weighting of environmental indicators around the concept of critical natural capital (section 8.3). Finally, conclusions are drawn for the specific case of sustainability assessment of technologies, and a framework for the integration of indicators is proposed (section 10).

8.1 An Overview of Decision-Making Tools for Integrative Assessments

8.1.1 Monetary Valuation Methods and Cost-Benefit Analysis

Valuation techniques aim at translating all of the indicators into monetary units to later do the sustainability assessment by means of economic assessment tools, such as cost-benefit analysis (CBA). Several different methodologies have been developed for the economic valuation of non-marketed environmental assets and services. These include contingent valuation (Ciriacy-Wantrup, 1947), the travel cost method (Hotelling, 1949), hedonic pricing, and avoided damage cost approaches, among others. However, these techniques are confronted with a number of methodological problems. Hanley, (1992) provides a thorough account of these problems. These are summarized in Table 8.1.

Valuation Methodology	Drawbacks /Limitations
Contingent Valuation (Based on surveys asking people directly about their willingness to pay for environmental services)	Biased responses in surveys (information provided to respondents, strategic behaviour). Bid's aggregation method The choice of welfare measure
Travel Cost Method (Based on the assumption that the time and money that people spend to get to a recreation site represent the value of the place)	Value of time? Respondents who visit more than one site in a day out. Limited applicability
Hedonic Pricing (Based on the influence that the availability of some environmental services have on market prices, usually housing prices)	Assumption of efficient market Assumptions about future (rather than current) environmental quality levels Limited applicability (housing market / labour market)
Avoided Damage Cost (Based on the cost to avoid the loss or to provide substitutes to lost environmental services)	Underestimation due to imperfect substitution Limited applicability

Table 8.1: Valuation methods and its limitations. Based on (Hanley, 1992).

However, the drawbacks of monetary approaches to be applied for sustainability assessments go beyond the limitations of the particular choice of a valuation method. Cost-benefit analysis fails to capture the complexity of environmental and social systems by reducing all the information into an economic value (Norgaard, 1989) (Hanley, 1992). Munda, (2000) criticises the application of cost-benefit analysis for sustainability assessments in these terms: *'The use of precise, quantitative data based on monetary valuations (such as market prices) where complexity and uncertainty are pervasive, can be misleading. There is a certain degree of comfort associated with precise numbers despite the fact that the unidimensional answer can lack any actual relevance, i.e. being precise but wrong. Quantitative data is often erroneously regarded as more rigorous than qualitative information. By presenting results in monetary terms, this misconception is reinforced by the message that quantitative results are 'true' representations while qualitative data are less important and more uncertain'.*

More importantly, the translation of every indicator into a monetary value, and the subsequent cost-benefit analysis implicitly assumes complete substitution between human-made and natural capital. If complete substitution is not possible, for instance, when irreversible natural effects occur, a cost-benefit analysis will potentially lead to unsustainable solutions (Janssen & Munda, 1999).

In light of all the above, I argue that cost-benefit analysis – although undeniably useful as an input in several decision-making situations – fails to provide a comprehensive framework to address the complexity of integrative sustainability assessments.

8.1.2 Multi-Criteria Decision Making (MCDM)

A multi-criteria analysis (MCA) is a decision-making methodology that can be used when a number of alternatives have to be evaluated according to a set of different criteria. This is the kind of decision-making tool that is required for the case of the sustainability assessment of technologies, as defined in section 6.2, when different technological alternatives providing the same *functional unit* are assessed according to a wide variety of sustainability indicators or criteria. Belton & Stewart (2002) defined MCA as ‘formal approaches which seek to take explicit account of multiple criteria in helping individuals and groups explore decisions that matter’.

Multi-criteria methodologies try to consider simultaneous multiple conflicting criteria, for instance maximizing environmental quality, minimizing costs, as well as making sure that everybody gets a fair share (Janssen & Munda, 1999). MCA is capable of integrating normative judgements (e.g. stakeholder opinion) together with technical expertise (e.g. quantitative data) in a unique framework of decision (Buchholz, Rametsteiner, Volk, & Luzadis, 2009). In general, in a multicriteria problem, there is no solution optimising all the criteria at the same time, and therefore the decision-maker has to find compromise solutions (Martínez-Alier, Munda, & O'Neill, 1998). MCA assists complex decision problems in the following ways (Beinat, 1995):

- It makes it possible to analyse the trade-offs between different objectives and concerns, thus supporting the analysis of the pros and cons of different options in a transparent way;
- The effects of alternative options can be presented in a variety of forms, such as monetary units, physical units, qualitative judgements, etc;
- It offers a framework for the exploration of the objectives and concerns of decision actors, making it possible to understand and justify the main issues involved in a decision and the interests of the actors involved;
- It makes it possible to consider the different positions of different decision actors; thus identifying and addressing potential conflicts at an early stage of the decision process;
- It offers the possibility of analysing the sensitivity and robustness of different choices against the effects of uncertainty and on the basis of different future scenarios.

Multicriteria evaluation techniques can be criticised on the basis that the trade-offs required to calculate the best option among the alternatives are not fundamentally different from a monetary valuation followed by a conventional cost-benefit analysis. However, I will argue that the usefulness of MCA goes beyond the mere utilitarian purpose of calculating the ‘best’ alternative. It provides a framework to structure the decision-making process, and it reveals the underlying contradicting goals. ‘*From an operational point of view, the major strength of multicriteria methods is their ability to address problems marked by various conflicting evaluations. […] The main advantage of multicriteria models is that they make it possible to consider a large number of data, relations and objectives which are generally present in a specific real-world decision problem, so that the decision problem at hand can be studied in a multidimensional fashion’* (Martínez-Alier, Munda, & O'Neill, 1998).

A multi-criteria decision problem of this kind can be framed in the following way: The set T defines a series of n technological alternatives (T_1, T_2, $T_3 \ldots T_n$), while C (C_1, C_2, $C_3 \ldots$ C_m) is a set of m criteria under which the different alternatives are judged. With these two sets, a so-called ‘decision matrix’ can be built. Each of the values in this matrix represents the assessment of one of the technological alternatives according to a specific sustainability criterion.

The choice of the 'best' technological alternative can be based on different rationales to treat the values in the decision matrix. In this sense, Yoon & Hwang, (1995) make a clear distinction between compensatory and non-compensatory methods. This distinction is made on the basis of whether low scores in one criterion can be compensated with high scores in other criteria or not.

<u>Compensatory Approaches:</u>

Compensatory approaches assume full compensability between criteria. In other words, trade-offs between criteria do exist. These trade-offs are ultimately defined by the weight that is given to each criterion. The weights define the '*marginal rate of substitution'* between the performances of the technology on the different criteria. Compensatory approaches differ on the methodology used for the aggregation of results:

***Simple Additive Weighting*:** This is the most widely used MCA method. Scores for each alternative are obtained by adding the contributions of each of the criteria. This is achieved by multiplying the scores on each criterion by the weight given to that criterion, and then adding all those weighted scores together. A normalization process is required in order to enable the addition of the scores.

$$ScoreT_n = \sum_{i=1}^{m} w_i \bullet c_i$$

Weighted Product Method: In this method, scores for each alternative are obtained by multiplying the values for each criterion. The weights are the exponents of each multiplier (positive or negative). In this case, no normalization process is required.

$$ScoreT_n = \prod_{i=1}^{m} c_i^{W_i}$$

There are different methodologies to arrive to the required weighting factors for the two previously discussed methodologies:

- ***Expert panels*** (using Delphi approaches, or other methodologies for panel decision-making)
- ***Distance-to target methodologies***
- ***Stakeholder involvement.***
- ***Damage-based approaches***
- **…**

Section 8.3 discusses an exemplary methodology to obtain weighting factors for environmental indicators with a damage-based approach.

***Analytic Hierarchy Process**:* Developed by Thomas L. Saaty in the 70's, the analytic hierarchy process is a MCA approach in which factors are arranged in a hierarchic structure (Saaty, 1990). This methodology decomposes a complex decision-making problem into smaller elements by constructing a hierarchy, starting from the overall goal of the decision, descending to criteria, sub-criteria, and finally the alternatives. Weights are generated endogenously by implicitly revealing preferences in pairwise comparisons of alternatives.

Non-Compensatory MCA Methods

These methods are used when the decision maker does not allow compensation between criteria via weighting factors. Yoon & Hwang, (1995), provides a classification of MCA non-compensatory approaches. I consider for further discussion the following:

1. *Dominance:* Consisting in the direct analysis of the decision matrix, looking for dominant alternatives. However, the likelihood of an alternative dominating or being dominated by all others is very small (Department for Communities. Local Government: London, 2009).

2. *Satisficing Methods:* They are used to select acceptable/unacceptable alternatives depending on a condition that has to be satisfied. There are two satisficing methods: The conjunctive model eliminates alternatives that fail to reach externally set levels of performance on each of one or more criteria. The disjunctive model selects an alternative when it meets a minimum threshold level of performance on at least one criterion (Department for Communities. Local Government: London, 2009).

3. *Lexicographic Ordering:* In lexicographic elimination, all options are first compared in terms of the criterion deemed most important (Department for Communities. Local Government: London, 2009). The best alternative according to this criterion is the selected one. If there is a tie, the second criterion in importance is considered and so forth, until a selected alternative is found.

8.2 Implications of an Integrative Sustainability Assessment

As it was mentioned earlier, an integrative sustainability assessment requires taking into account a wide variety of indicators, coming from the different 'dimensions' underlying the concept of sustainable development. This can be done via an informed analysis of a multiple indicator 'scoreboard' or by aggregating all these indicators into synthetic indices.

Several relevant aggregated indices have been proposed to address different aspects of sustainability. Some examples of these aggregated indices are:

- The *Human Development Index* (HDI), introduced by the UNDP in 1990, combining three indicators: life expectancy, income and level of education (UNDP, 1990).
- The *Index of Sustainable Economic Welfare* (ISEW), a monetary index pointing at correcting GDP by taking into account social and environmental costs (Daly & Cobb, 1989).
- The *Ecological Footprint,* an aggregated assessment of human pressure on the environment in terms of productive land area (Wackernagel & Rees, 1996).

The use of aggregated synthetic indicators has both advantages and drawbacks. From the point of view of the decision-makers, Constanza, (2000) discusses them in the following terms: '*The costs of an aggregate indicator are that [...] one can be ignorant of where the numbers came from, how they were aggregated, the uncertainties, weights, and assumptions involved, etc. The beauty of the aggregate indicator is that it does that job for them'* (Constanza R. , 2000). Munda, (2005) also discusses the feasibility of aggregated indices from a methodological perspective: *'All the indexes are based on the assumptions that a common measurement rod needs to be established for aggregation purposes (money, energy, space, and so on). This creates the need of making very strong assumptions on conversion coefficients to be used and on compensability allowed [...] The mathematical aggregation convention behind an index thus need an explicit and well thought formulation'*.

Integration does not necessarily require aggregation

An aggregation process consists in condensing the information coming from all the indicators of sustainability into one single synthetic indicator or sustainability index. However, an integrative assessment of sustainability does not necessarily require the aggregation of indicators into a single score synthetic index, nor we can emphatically conclude that all the complexity around the concept of sustainable development can be summed up into a single indicator. Baneth, (2008) used the analogy of a plane cockpit to point this out in the following terms: *'A pilot flies an aircraft using data supplied by a large number of instruments and that data cannot be summed up in a single indicator'*. The aircraft metaphor can be useful in our analysis of the process of integration of sustainability indicators. Pilots carry out an integration process, i.e. they need to interpret all the data coming from all of the cockpit instruments in order to fly the plane safely to destination, i.e. for decision-making. They require instantaneous access to information on altitude, inclination, horizontal and vertical speed, temperature of the engines, flap angles, etc. However, for the purpose of flying the plane, aggregating all the information in the cockpit into one single indicator would be of very little use. This example illustrates how an integrative process does not necessarily require the aggregation of information into a single-score index.

What 'utility' do we want to maximize?

However, it is indeed mathematically possible to summarize all the information in the cockpit into aggregated indicators. This can be done in several different ways depending on the question that we need to answer: is the plane on time/ not on time? Is the plane flying safe? How satisfactory is the passenger experience? Etc. This illustrates how aggregation processes make sense only when the purpose of the aggregated information is clearly defined, because whenever aggregation is performed, valuable pieces of information diffuse in the process. But, what is the purpose or 'utility' that we want to maximize when obtaining an aggregated index of sustainability? The answer is: we pursue several forms of utility simultaneously. We want the plane to fly safely (environmental sustainability), we want the plane to be technologically advanced, silent, fast and fuel-efficient (economic dimension) and we – ultimately – want all the passengers to enjoy the flight (social dimension). The problem resides in the impossibility of maximizing all the identified 'utilities' at the same time. In his *Tragedy of the Commons*, Garret Hardin (1968) criticised Bentham's utilitarian motto *'the greatest good for the greatest number'* for this very same reason: It is mathematically impossible to maximize for two – or more – variables at the same time. Thus, a 'utility function' – a rationale for the decision – has to be defined before any aggregation process is done. More importantly, the definition of this utility function is intimately connected with the sustainability paradigm and underlying values that inform the assessment (see section 7.1).

The metaphor of the plane also helps us to illustrate how the aggregation process can become meaningless when compensation across dimensions is allowed in all circumstances: Does it make sense to say that the flight is equally satisfactory if passenger experience increases at the expense of decreasing flight altitude? When a defined safe altitude threshold is surpassed, our plane and our passengers are in real danger, regardless of how much enjoyment people are having in the cabin. The ultimate goal of increasing passenger satisfaction only makes sense once minimum safety standards have been met. In a similar fashion, the ultimate goal of social performance (social sustainability) cannot be simply aggregated with environmental sustainability. Although it is true that both are linked in several ways, it is also undeniable that there are certain environmental thresholds – as they were discussed in section 7.4 – that should not be surpassed regardless of the associated short-term social benefits. Thus, environmental preservation is not only a variable influencing the sustainability assessment, but also a required condition for a satisfactory socio-economic performance. For this reason, full compensation between the socio-economic and environmental indicators should not be allowed. Both should be analyzed separately and they necessarily have to be given different priorities in the assessment.

<u>Three dimensions of sustainability, why?</u>

As it was previously discussed in section 6.1, understanding *sustainable development* as a three dimensional concept (environmental, social and economic dimensions or pillars) has become widely accepted (IUCN, 2006) (UN, 2005). In fact, the two existing approaches for sustainability assessments of products/technologies that were discussed in section 5 – PROSA and CALCAS – follow this conceptual framework. Fig. 8.2 shows this traditional three-dimensional framework of sustainable development as overlapping circles.

Fig. 8.2: Three-dimensional view of Sustainable Development. Overlapping circles model. Source: (IUCN, 2006)

Looking at the concept of sustainable development from this perspective intuitively leads to a vision in which an integrated sustainability assessment comes from the aggregation of the results coming from the independent assessments of each dimension by means of weighting factors. However, although it is undeniably true that there are always environmental, economic and social issues at stake when performing a sustainability assessment, that does not imply that those should be considered at the same level of analysis, nor that they should be considered 'dimensions'. I will consequently argue that this conceptual view for integration might be misleading our sustainability assessments, at least for the following reasons:

Firstly, it intrinsically assumes that environmental preservation, social welfare, and economic wealth are – if not weighted equally – at the same level of analysis. Depicting the environment, the economy, and society as overlapping circles is far from being rooted in physical reality, as it denies fundamental dependencies among these systems. On the one hand, the social system – the aggregation of all human beings – is undeniably a sub-system within the global environment. On the other hand, there is no economy without a society that creates it (Mauerhofer, 2008). Besides, both sub-systems – society and its associated economic activity – are ultimately dependent on the environment (Daly H. E., 1997). Fig. 8.3 shows an alternative depiction of the three pillars of sustainability that acknowledges these relations of dependence[1] (EEA, 1999).

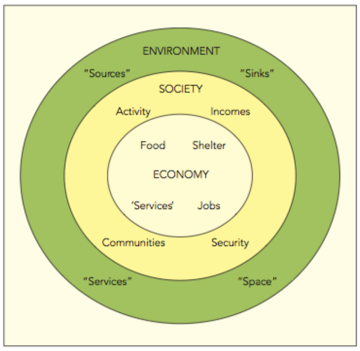


Fig. 8.3: Three-pillars of Sustainable Development. Embedded circles model. Source: (EEA, 1999)

Secondly, the goals that are pursued along the three components of sustainability are fundamentally different in nature. Let us analyze for a moment the composition of the phrase *'Sustainable Development'* itself: On the one hand, the term *Sustainable* – ability to sustain – provides a set of conditions or restrictions to be respected in order to make *development* possible in the first place. Section 7.3 discussed the implications of how strong these restrictions should be. On the other hand, the term *Development* refers to the extent to which social/human aspirations are met. It has been defined as 'a planned change, cultural, social, economic, political or ecological in character, towards an improvement in the quality of life' (Dias de Avila-Pires, Mior, Porto Aguiar, & De Mello Shlemper, 2000). The term *development* encompasses both the social and economic dimensions, therefore, to measure *Development* requires taking into account economic indicators (e.g. GDP per capita) as well as social indicators (e.g. life expectancy, literacy rate / educational level, etc.). However, there is something contradictory about the terms 'social sustainability' and 'economic sustainability'; in fact, the ultimate goal is not just to 'sustain' the social and economic systems, but to make them thrive, to obtain the maximum possible levels of social welfare derived from social and economic improvements. In conclusion, while environmental sustainability can be defined as a set of *conditions/restrictions* for the quality of the environment for human survival – ability to

[1] It is important to note that this representation depicts the economy as a subsystem of society. I consider more appropriate the approach taken in the conceptual framework proposed in section 6.2, where technologies are conceptualized as a form of economic capital, which enables the interaction between the environmental and the social systems.

sustain – the social and economic ‘dimensions’ of sustainability are a set of functions – welfare/utility – which we are supposed to *maximize*.

Thirdly, (related to the previous one) I will argue that the conflicting goals behind the concept of sustainable development cannot be boiled down satisfactorily to a one-dimensional ‘1-10’ index of sustainability; Section 7.4 discussed minimum levels of environmental capital as a condition for environmental sustainability. Arguably, similar minimums can be defined for social progress (United Nations, 2000). However, there are to this date no known maximums for social and economic progress. Therefore, what is a ‘10’ along the social and economic dimensions? On the other hand, any state that respects the critical natural capital thresholds discussed in section 7.4 could arguably be considered as strictly *sustainable* along the environmental dimension.

We can conclude from the three arguments expressed above that to conceive an integrative sustainability assessment simply as a process of aggregation across the three dimensions to obtain a single score of sustainability is very likely to result in a distorted view of reality. This is not to deny that environmental, economic and social aspects are to be considered. Instead, I will argue that an integrative process is required, one that goes beyond the concept of aggregation across ‘dimensions’, and one in which those domains that constitute critical conditions for sustainability are assessed differently from those domains that are to be maximized.

This conclusion is in line with that drawn in sections 7.3 and 7.4, about the non-compensability of certain forms of critical natural capital and the scientific soundness of the strong sustainability paradigm.

8.3 Integration of Critical Natural Capital in the Sustainability Assessment

The possibility of making the concept of *strong sustainability* operational around the current scientific knowledge on critical environmental services was previously proposed in section 7.4. This requires:

1. The identification of an appropriate set of indicators to evaluate the current state of these environmental services.
2. To define objective aggregation methodologies in order to provide an overall assessment of the technology under study with regards to these critical environmental services.

Rockstrom et.al, (2009) defines a set of environmental boundaries that should not be transgressed in order to prevent unacceptable environmental change. Rockstrom's approach highlights the nonlinear behaviour of most environmental systems and therefore the need to observe critical thresholds.

PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	-1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Fig. 8.4: Environmental thresholds and their current situation according to Rockstrom et.al.

The environmental impact of any *functional unit* provided by a technology can arguably be translated, structured, and evaluated according to the corresponding impact on each of these boundaries. Different technologies will have different impacts on each of these boundaries. This inevitably leads to an aggregation process, a decision based on a multiple set of criteria (MCDM). Therefore, the choice for a certain technology against its alternatives for the same *functional unit* should be based on an objective prioritization of these boundaries. Rockstrom's approach does not provide a basis for this prioritization. He intrinsically concludes that all the identified boundaries are equally critical for the preservation of a liveable environment. He assumes that transgressing any of them could trigger dramatic environmental change *'leading to a state less conducive to human development'* (Rockstrom_et.al, 2009). However, there are other options to address this prioritization process that are discussed next:

Weighting factors can be derived using a so-called 'distance-to-target' (DTT) approach, i.e. to give higher priority to those indicators whose values are closer to the environmental boundaries defined by Rockstrom et.al. This approach is confronted with at least the following two inconveniences:

1) Some of the indicators have already gone beyond the corresponding limit identified by Rockstrom et.al, while others are still below the limit. If the prioritization were merely based on the DTT at the moment when the assessment is performed, then what would be the adequate weight for those indicators that are already above the limit? Furthermore, should those indicators below the limit be weighted at all when there are others already over the limit that should enjoy higher priority?

2) The DTT approach does not capture the long-term behaviour of the indicator. The potential damage on the environmental system derived from trespassing the boundaries, not only depends on the current situation of the indicator, but also on the expected long-term trend. Indicators currently below the limits, but showing a worrying long-term behaviour, might be as potentially damaging as indicators currently beyond the limits showing a less dramatic trend.

These two inconveniences of a strict DTT approach highlight the need to support the weighting process in the long-term potential damage for each of the impact categories, regardless of the current value of the boundary indicator. Capturing long-term trends in the sustainability assessment of technologies is particularly important for three main reasons: Firstly, the process of diffusion of new technologies requires time. Public policies, R&D programmes, corporate investment and employment will rely on the long-term validity of the sustainability assessment. Secondly, the environmental variables chosen by Rockstrom et.al show considerable inertias that cannot be neglected in the evaluation. Finally, structural changes and transformation of relevant consumption patterns within the societal system also take place in the long-term.

In order to address the inconveniences of a pure DTT approach, a new proposal is put forward next. I will refer to this methodology as the 'accumulated damages' (AD) approach. According to this, a higher priority should be given to those indicators showing the worse accumulated environmental damage for the period of study. The method assumes that any variable above preindustrial levels[1] induces certain impact on the environment and that environmental damage increases with accumulated time[2]. Therefore, accumulated damages can be estimated by multiplying the difference between the current value of the control variable and its preindustrial level by the period of time that this difference persists (see Fig. 8.5). Individual weighting factors for the indicators can be derived by comparing 'expected long-term damages' with 'acceptable long-term damages' derived from Rockstrom et.al for each of the variables and for a given period of time.

The first step is to define the time frame for the analysis. As it was pointed out before, a long-term perspective is required. For the purpose of the sustainability assessment of technologies, a minimum time scope of one generation i.e. 30 years[3] is considered acceptable to capture the time required for the diffusion of new technologies.

---

[1] The term 'above' is used here in a broad sense to describe the effect of human activity on environmental variables. In some cases the effect is an increase in the variable e.g. GHG, fixed N_2, etc, while other variables are reduced by human activity e.g. biodiversity stock, ozone layer, etc.

[2] It is assumed for the purpose of this project that the damage increases linearly with time.

[3] Definition of generation according to the Oxford Dictionary (www.oxforddictionaries.com)

The second step is to evaluate the long-term damages. In order to do this, three scenarios are defined for each of the variables/indicators involved. Firstly, a 'business as usual' (BAU) scenario defines how the situation is expected to unfold considering the present status of the variable as well as the expected average rate of variation during the period. Secondly, a 'Rockstrom boundary' scenario is defined based on the environmental limits defined by Rockstrom et.al. Finally, a 'preindustrial scenario' is constructed based on the estimated preindustrial values of the variables. Evaluating the 'Rockstrom' scenario against the 'preindustrial' scenario provides the so-called 'acceptable damage'. The 'acceptable damage' for each of the indicators is defined as the unitary damage, and it serves as the basis for the subsequent normalization process (see Fig. 8.5 and Eq. 8.1).

The third step is to obtain the weighting factors. Each of the analyzed variables will return a value above or below one. Values bigger than one correspond to variables with an expected long-term damage bigger than the acceptable damage. In turn, values lower than one correspond to variables with an expected damage lower than the acceptable damage.

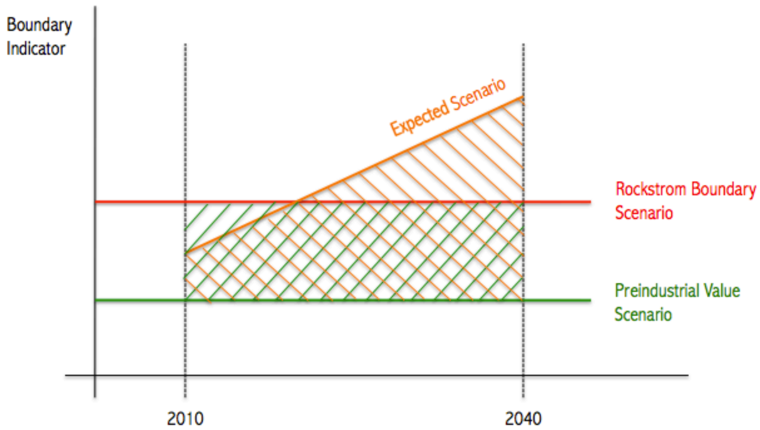
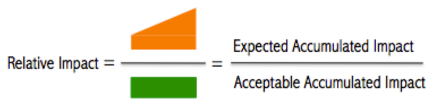


Fig. 8.5: Accumulated Damages (AD) approach. Scenarios

Fig. 8.5 shows the accumulated impacts of the different scenarios. The preindustrial scenario is assumed to produce no accumulated damage. The area below the expected scenario[1] represents the expected accumulated damage for the period of study. The area below the Rockstrom scenario represents the acceptable accumulated damage. It is important to note that the result of this evaluation is non-dimensional. It shows the importance of the environmental transgression in relative terms, comparing it with the maximum acceptable damage derived from Rockstrom's boundaries.



Eq. 8.1: Relative damage calculation (criticality)

The resulting weighting factors describe how critical the situation is for each of them and for the considered time period. They are shown in Table 8.2 and

Table 8.3.

[1] For the purpose of this exemplary case, values in 2040 are assumed to stabilize at current levels.

		Preindustrial	Rockstrom Boundary	Value in 2010	Expected Value 2040	Accepted Accumulated Impact	Expected Accumulated Impact	Linear Normal. Criticality: BAU/Rockstrom	Weighting Factor
Nitrogen cycle	N2 removed from atmosphere (Mton/year)	0	35	121	121	1050	3630	3,457	**17,77%**
Phosphorus cycle	P flowing to oceans (Mton/year)	1	11	9	9	300	240	0,800	**4,11%**
Freshwater use	Km3/year	415	4000	2600	2600	107550	65550	0,609	**3,13%**
Land use	% land cover converted to cropland	0	15	11,7	11,7	450	351	0,780	**4,01%**
Biodiversity loss	Extinction rate (species/million species*year)	1	10	100	100	270	2970	11,000	**56,53%**
Ozone layer	Stratospheric ozone depletion (Dobson unit)	290	276	283	283	420	210	0,500	**2,57%**
Climate regulation	CO2 Concentration ppm	280	350	387	387	2100	3210	1,529	**7,86%**
Acidification	Mean saturation aragonite	3,44	2,75	2,9	2,9	20,7	16,2	0,783	**4,02%**
Atmospheric aerosols loading	-	-	-	-	-	-	-	-	-
Chemical pollution	-	-	-	-	-	-	-	-	-
Time Scope (years)							Total	19,458	1,000
30									

Table 8.2: Weighting factors derived from critical environmental indicators[1] (biodiversity and acidification included).

The results show a particularly high value of the weighting factor for biodiversity (56.3%). This is consistent with the methodology followed, as the value for biodiversity loss in 2010 was already one order of magnitude higher than the boundary assigned by Rockstrom et.al, while the rest of the indicators are still in the same order of magnitude as their corresponding boundaries. The linear normalization process that has been used allows this differences in the resulting weighting factors. However, if a logarithmic normalization process is followed, the differences in the weighting factors are less dramatic, while keeping the same priority ranking:

		Preindustrial	Rockstrom Boundary	Value in 2010	Expected Value 2040	Accepted Accumulated Impact	Expected Accumulated Impact	Logaritmic Normal. Criticality: LOG (BAU) / LOG (Rockstrom)	Weighting Factor
Nitrogen cycle	N2 removed from atmosphere (Mton/year)	0	35	121	121	1050	3630	1,178	**14,12%**
Phosphorus cycle	P flowing to oceans (Mton/year)	1	11	9	9	300	240	0,961	**11,52%**
Freshwater use	Km3/year	415	4000	2600	2600	107550	65550	0,957	**11,47%**
Land use	% land cover converted to cropland	0	15	11,7	11,7	450	351	0,959	**11,50%**
Biodiversity loss	Extinction rate (species/million species*year)	1	10	100	100	270	2970	1,428	**17,12%**
Ozone layer	Stratospheric ozone depletion (Dobson unit)	290	276	283	283	420	210	0,885	**10,61%**
Climate regulation	CO2 Concentration ppm	280	350	387	387	2100	3210	1,055	**12,65%**
Acidification	Mean saturation aragonite	3,44	2,75	2,9	2,9	20,7	16,2	0,919	**11,02%**
Atmospheric aerosols loading	-	-	-	-	-				
Chemical pollution	-	-	-	-	-				
Time Scope (years)								8,344	1,000
30									

Table 8.3: Weighting factors derived from critical environmental indicators (logarithmic normalization).

[1] The column 'criticality' is non dimensional. It shows the relative size of the expected accumulated impact compared to the admissible impact defined by Rockstrom's boundaries. The accumulated impacts are calculated multiplying the values of the indicator by the time scope of the analysis (30 years).

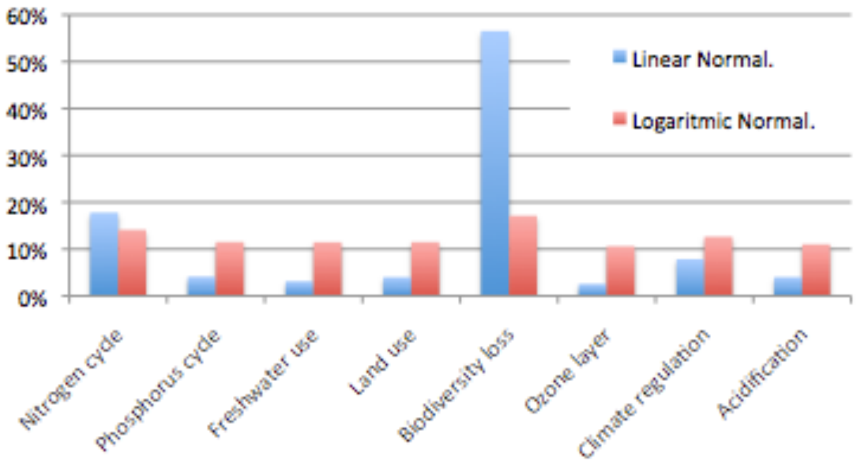


Fig. 8.6: Weighting factors based on linear and logarithmic normalization.

This exemplary case shows how it is indeed possible to support the weighting procedure in objective criteria, such as the expected accumulated damage in each of the critical environmental boundaries defined by Rockstrom et.al. However, these environmental boundaries do not match the impact categories of most environmental LCA frameworks[1]. This is required in order to assess the impact of the *functional unit* according to these weights. For this purpose, an allocation procedure still has to be defined, i.e. a transfer function that translates the LCA impact categories into measurable impacts on these boundaries. This should be a matter of further research.

The proposed methodology shows how the definition of environmental thresholds can provide a rationale for the weighting of environmental impacts. This methodology allows us to establish priorities among the different environmental impact categories based on their relative impact on the Critical Natural Capital. In turn, it also opens possibilities to make the *strong sustainability* paradigm operational. However, this weighting methodology still follows a compensatory approach, i.e. bad performance in one of the indicators can be compensated with good performance in others.

In order to fully implement the *strong sustainability paradigm* into the assessment, the concept of Critical Natural Capital should be integrated through non-compensatory approaches. For this purpose, the environmental thresholds defined by Rockström at global level, would have to be allocated at the level of the relevant functional unit. However, as it was discussed in section 6.2, this requires, in principle, a political decision. An option to shortcut this limitation may be to base the allocation process on an empirical analysis of the current impact of the different economic sectors on each of the environmental boundaries. This certainly constitutes an interesting line for further research.

[1] For more information on LCA frameworks: Institute for Environment and Sustainability, J. (2010). *ILCD Handbook. International Reference Life Cycle Data System.* European Commision.

9 Conclusions & Discussion

RQ1: ***Is it possible to build a sound scientific case for a particular sustainability paradigm as a basis to support the sustainability assessment of technologies?***

The ideal of Sustainable Development – on which any sustainability assessments should be based - remains a contestable concept:

The concept of sustainable development still is – and possibly will always be – in dispute. It has purely normative components such as the desirable reach of intragenerational equity, the allocation of intrinsic rights to nature, or the level of risk that societies should bear with regards to the degradation of the environment. These components clearly fall in the realm of politics. Still, science can and should play a key role in informing the associated decision-making processes.

However, the concept of sustainable development also has an objective core. We can objectively analyze what are the systems involved in the concept of sustainable development as well as the relevant interactions and dependencies between them. Furthermore, there are objective truths about the well being of humans within the social systems (e.g. access to minimum levels of food, health care and sanitation, institutional stability and freedom, etc.) that can be supported in strong empirical evidence, regardless of our particular political stance. All these components of the ideal of sustainable development can and should be dealt with within the realm of science.

In this sense, there is abundant supporting evidence to conclude that the Strong Sustainability paradigm is appropriately rooted on empirical evidence, and therefore it provides a useful cornerstone for sustainability assessment.

There are two main reasons for this:

a) It acknowledges the ultimate dependence of the social and economic systems on some forms of natural capital. Since natural capital is required for the production of manufactured (human-made) capital, the latter can never be a complete substitute for the former. Constanza and Daly (1992) provide further argumentation for this in the following terms: *'production is a transformation process in which a flow of natural resource inputs is transformed into a flow of product outputs by means of labour (human capital) and manufactured capital. Natural resources are that which is being transformed into products, manufactured and human capital are what is effecting the transformation. The relationship is overwhelmingly one of complementarity, not substitutability.*

b) It is a more precautionary option in light of the lack of complete knowledge about the behaviour and ultimate resilience of the environmental systems. In this sense, Ekins et. al. (2003) highlighted that the destruction of manufactured capital is very rarely irreversible, whereas irreversibility is common in the consumption of natural capital e.g. extinction of species, climate change, combustion of fossil fuels, etc. Furthermore, the precautionary principle was endorsed by the UN in the Rio Declaration: *'In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or 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).

RQ2: ***What is the most appropriate methodology for the integration of indicators across the various dimensions of sustainable development?***

It was concluded in the answer to the first research question that Sustainable Development is a multi-objective concept in which contradicting forms of utility are pursued.

It has been shown in section 8.1.1 how economic valuation methodologies fail to provide a comprehensive framework to address the complexity of integrative sustainability assessments. Furthermore, cost-benefit analysis techniques implicitly assume complete substitution between human-made and natural capital.

Section 8.1.2 shows how multi-criteria decision-making techniques can assist in overcoming some of the limitations of economic valuations, providing a valuable framework for integrative sustainability assessments and decision-making. MCA is capable of integrating normative judgements (e.g. stakeholder opinion) together with technical expertise (e.g. quantitative data) in a unique framework of decision (Buchholz, Rametsteiner, Volk, & Luzadis, 2009).

It has been also shown in this work that some of the inherent objectives of sustainable development can be compensated/traded by others e.g. creation of economic wealth in the form of durable capital or technological knowledge can pay-back in the long term the depletion of some natural resources (Hartwick, 1977). However, the failure to meet some objectives – such as the preservation of life-supporting services provided by natural capital – cannot be compensated by meeting other objectives. Some forms of natural capital are non-substitutable (Constanza & Daly, 1992). For this reason, non-compensatory MCA methodologies will be required at some point of the decision-making processes.

Furthermore, section 8.2 has illustrated how an integrative process does not necessarily require aggregation, since in some cases, particularly when divergent forms of utility are pursed simultaneously, the aggregation of indicators provides very little or no useful insight. Moreover, given the nature of the dependence relations and the conflicting goals that are pursued in the different domains of sustainability, to conceive an integrative assessment simply as a process of aggregation into a single score may conduce to a distorted view of reality.

In light of all the above, an integrative process is required, one that goes beyond the concept of aggregation, and one in which those domains that constitute critical conditions for sustainability are assessed differently from those domains that are to be maximized. Section 10 is dedicated to outline a proposal of this integrative framework.

9.1 Recommendations

1. **The sustainability assessment of technologies should be performed in terms of their contribution to the sustainability of the environmental and socio-economic systems, at the level of the *functional unit*, rather than pursuing an assessment on the intrinsic sustainability of the technology itself.**

   It is imperative to formulate the question on the sustainability of technologies in approachable terms. For this purpose, section 6.2 discussed the role that technologies play in the pursue of sustainable development. We are very unlikely to give a definitive answer to the question: Is the technology X sustainable***?*** Technologies are just capacities that are conceived by societies to transform and use natural resources and services in our best advantage. 'Technology is the link, not the aim' (Guinée, Huppes, Heijungs, & van der Voet, 2009). The ultimate concern is the sustainability of the social and environmental systems. In this sense, technologies act as an interface between the environment and us. They are the means to provide the ends. The environmental system can be in a sustainable or unsustainable state depending on a number of control variables to be defined e.g. radiative forcing in the atmosphere, biodiversity loss rate, land use change rate, etc. Accordingly, we can define state variables for the societal system: life expectancy, educational level, income per capita, declared happiness, etc. However, to assess the influence that technologies have on the sustainability of the systems, the analysis can only be done at the level of the *functional unit* that the technology in question provides to society (see the proposed conceptual framework in Fig. 6.2).

   Therefore, it is more appropriate to formulate the question on the sustainability of the technologies in the following terms: *To what extent the consumption of a functional unit of technology X contributes to the sustainability or un-sustainability of the environmental and societal systems?*

10 Integration of Sustainability Indicators: A Proposal

Section 8.2 concluded that the simple aggregation of indicators across the traditional three dimensions of sustainability can give us a distorted view of reality, as it fails to capture the nature of the interactions and dependencies between the relevant systems. For this reason, an alternative framework for the integration of indicators is required. The proposed framework has the following features: Firstly, it is rooted in physical reality, in the sense that it acknowledges the ultimate dependence of the social system on the environmental system. It follows the same structure as the conceptual framework proposed in section 6.2, where the social and economic systems are depicted as subsystems of the environmental system. Secondly, it distinguishes those areas where aggregation of indicators might be allowed – i.e. where trade-offs between indicators can be defined either via objective scientific methods, expert judgement or stakeholder involvement – from those areas where there is enough scientific basis to state that full compensation should not be allowed (see section 7.3).

The integration of indicators has to be done at different levels. For the purpose of this proposal I will distinguish two 'axis' of integration:

On the one hand I consider the integration of indicators within the relevant systems, e.g. integration of environmental indicators to assess the environmental performance of a technology, and idem for the social and economic systems. Calculating the aggregated impacts on each of the systems require weighting across different impact categories. For instance, the impact of a certain technology in the natural capital includes its influences in the resource base, the waste sink capacity, the life-support systems and amenities[1]. These impact categories, in turn, may require aggregation of several indicators. Similar integration processes have to be carried out for the indicators of the societal and economic systems. Section 8.3 explored a feasible approach to perform this aggregation for process for the environmental system, supporting the calculation of weighting factors in objective data.

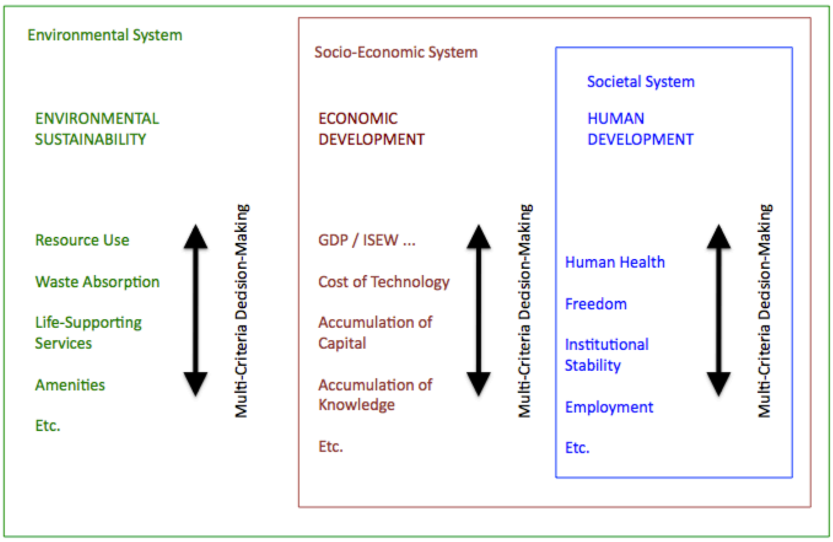


Fig. 10.1 Integration within relevant systems.

On the other hand, I will consider the integration of the results across systems, i.e. the decision-making process based on the integrated performances in each of the systems considered.

[1] Classification of natural capital assets according to Common, M., & Stagl, S. (2005). *Ecological Economics*. Cambridge: Cambridge.

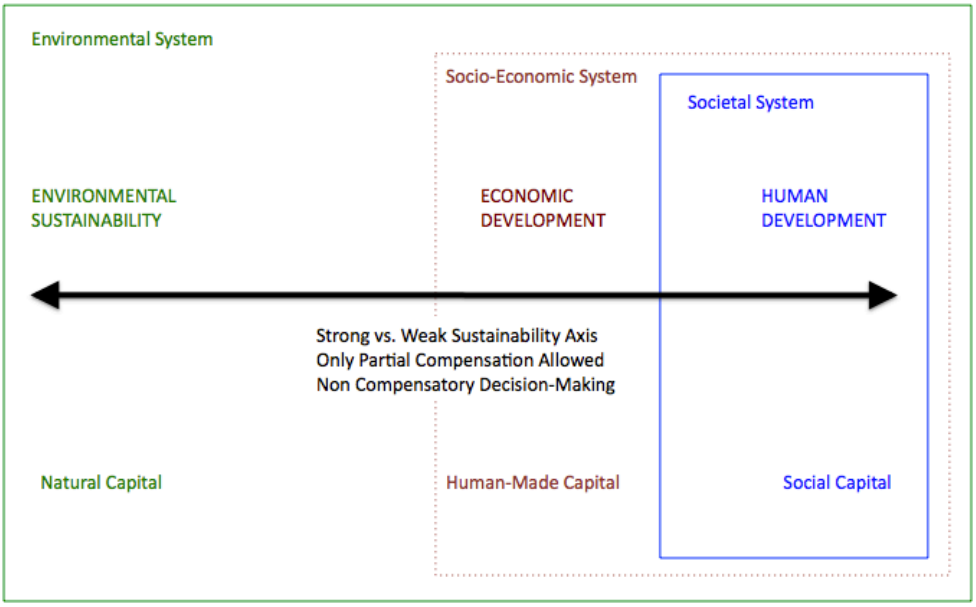


Fig. 10.2 Integration across relevant systems.

Fig. 10.2 shows in the same framework of decision the three relevant systems in any integrated sustainability assessment. The horizontal axis across them represents the line along which the tension between the weak and strong sustainability paradigms is resolved.

As it was discussed earlier in section 7.4, accepting the *strong sustainability* paradigm results in the acceptance of some environmental assets as critical for human survival and, therefore, 'non-negotiable'. This implies that traditional compensatory aggregation methodologies are not suitable for the assessment, since it is unacceptable to compensate these environmental impacts with possible societal or economic benefits. For this reason, the integration of indicators along this axis, should not allow full compensation. It is in this stage of the assessment where the non-compensatory MCA techniques discussed in section 8.1.2 may be considered to assist decision-making.

11 References

Baneth, J. (1998). Les indicateurs synthétiques de développement. *Futuribles , 231*, 5–27.

Beinat, E. (1995). *Environmental and Resource Planning: A Basic Introduction to Decision Support Methodologies.* Institute for Environmental Studies and Faculty of Economics. Vrije Universiteit Amsterdam.

Belton, V., & Stewart, T. (2002). *Multiple Criterial Decision Analysis. An Integrated Approach.* Boston: Kluwer Academic Publishers .

Benoît_et.al. (2010). The guidelines for social life cycle assessment of products: just in time! *International Journal of LCA , 15*, 156-163.

Boulanger, M. (2008). Sustainable Development Indicators: A Scientific Challenge, a Democratic Isuue. *Sapiens-Journal , 1* (1), 45-59.

Buchholz, T., Rametsteiner, E., Volk, T. A., & Luzadis, V. A. (2009). Multi Criteria Analysis for bioenergy systems assessments. *Energy Policy , 37* , 484–495.

Chertow, M. R. (2001). The IPAT Equation and Its Variants. Changing Views of Technology and Environmental Impact. *Journal of Industrial Ecology , 4* (4), 13-29.

Ciriacy-Wantrup. (1947). Capital Returns from Soil Conservation Practices. *Journal of Farm Economics , 29* (4).

Common, M., & Stagl, S. (2005). *Ecological Economics.* Cambridge: Cambridge.

Commoner, B. (1972). The environmental cost of economic growth. (R. G. Ridker, Ed.) *Population, Resources and the Environment* , 339–363.

Constanza, R. (2000). The dynamics of the ecological footprint concept. *Ecological Economics , 32*, 341-345.

Constanza, R., & Daly, H. E. (1992). Natural Capital and Sustainable Development. *Conservation Biology* , 37-46.

Constanza_et.al. (1997). The value of the world's ecosystem services and natural capital. *Nature* (387), 253-260.

Daly, H. E. (1997). *Beyond Growth: The Economics of Sustainable Development.* Beacon Press.

Daly, H. E. (1990). Sustainable Development: From Concept and Theory to Operational Principles. (Jstor, Ed.) *Population and Development Review , 16*, 25-43.

Daly, H., & Cobb, J. (1989). *For the common good: redirecting the economy toward community, the environment and a sustainble future.* Boston: Beacon Press.

De Groot, R., Wilson, M., & Boumans, R. (2002). A typology for the description, classification and valuation of ecsoystem functions, goods and services: Integrating Economic and Ecological Perspectives. *Ecological Economics , 41* (3), 393-408.

Department for Communities. Local Government: London. (2009). *Multi-Criteria Analysis: A Manual.* Department for Communities and Local Government: London.

Dias de Avila-Pires, F., Mior, L. C., Porto Aguiar, V., & De Mello Shlemper, S. R. (2000). The Concept of Sustainable Development Revisited. *Foundations of Science , 5*, 261–268.

Du Pisani, J. A. (2006). Sustainable development - Historical roots of the concept. (Taylor&Francis, Ed.) *Journal of Integrative Environmental Sciences , 3* (2), 83-96.

EEA. (1999). *Environment in the European Union at the turn of the century.* EEA European Environmental Agency. Office for Official Publications of the European Communities.

Ekins, P., Simon, S., Deutsch, L., Folke, C., & Groot, R. D. (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. *Ecological Economics , 44*, 165-185.

Finkbeiner_et.al. (2006). The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *International Journal of LCA , 11* (2), 80-85.

Finnveden_et.al. (2009). Recent Developments in Life Cycle Assessment. *Journal of Environmental Management , 91*, 1-21.

Foot, D. K. (2008). Easter Island: A case study of non-sustainability. *Greener Management Internationas* (48), 11-20.

Goodland, R. (1995). The Concept of Environmental Sustainability. *Annual Review of Ecology and Systematics , 26*, 1-24.

Gosseries, A. (2005). The Egalitarian Case Against Brundtland's Sustainability. *GAIA: Ecological Perspectives for Science and Society , 14* (1), 40-46.

Guinée, J., Huppes, G., Heijungs, R., & van der Voet, E. (2009). *Research strategy, programmes and exemplary projects on life cycle sustainability analysis (LCSA).* CALCAS (Coordination Action for Innovation in Life Cycle Analysis for Sustainability).

Hanley, N. (1992). Are There Environmental Limits to Cost Benefit Analysis? (K. Publishers, Ed.) *Environmental and Resource Economics* , 33-59.

Hardin, G. (1968). The Tragedy of the Commons. *Science , 162* (3859), 1243-1248.

Hartwick, J. M. (1977). Intergenerational Equity and the Investing of Rents from Exhaustible Resources. *The American Economic Review , 67* (5), 972-974.

Hediger, W. (1999). Reconciling weak and strong sustainability. *International Journal of Social Economics , 6*.

Heijungs, R., Huppes, G., & Guinée, J. (2009). *D15 – A SCIENTIFIC FRAMEWORK FOR LCA.* CALCAS (Coordination Action for Innovation in Life-Cycle Analysis for Sustainability).

Heijungs_et.al. (2010). Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. *Polimer degradation and Stability* , 422-428.

Holdren, J., & Ehrlich, P. (1974). Human Population and the Global Environment. *American Scientist , 62*, 288.

Hotelling, H. (1949). 'Letter' in An Economic Study of the Monetary Evaluation of Recreation in the National Parks. In W. D. Service. (Ed.).

Hueting, R., & Reijnders, L. (1998). Sustainability is an objective concept. *Ecological Economics* , 139-147.

Institute for Applied Ecology. (2007). *PROSA, Product Sustainability Assessment: Guidelines.* (Ö. I. e.V., Ed.) Öko Institut e.V.

Institute for Environment and Sustainability, J. (2010). *ILCD Handbook. International Reference Life Cycle Data System.* European Commision.

IUCN. (2006). *The Future of Sustainability Re-thinking Environment and Development in the Twenty-first Century.* IUCN International Union for the Conservation of Nature.

Jørgensen, A. (2008). Methodologies for Social Life Cycle Assessment. *International Journal of LCA , 13*, 96-103.

Jabareen, Y. (2008). A new conceptual framework for sustainable development. *Environment, Development and Sustainability* , 179-192.

Jahnke, M., & Nutzinger, H. G. (2003). Sustainability—a theoretical idea or a practical recipe? *Poiesis Prax* , 275-294.

Janssen, R., & Munda, G. (1999). 'Multi-criteria methods for quantitative, qualitative and fuzzy evaluation problems'. In J. v. Bergh, *Handbook of Environmental and Resource Economics* (pp. 837-850). UK: Edward Elgar.

Jollands, N., Lermit, J., & Patterson, M. (2003). The usefulness of aggregate indicators in policy making and evaluation: a discussion with application to eco-efficiency indicators in New Zealand. *XXXX* .

Kaufmann, R. K. (1995). The economic multiplier of environmental life support: can capital substitute for a degraded environment? *Ecological Economics , 12*, 67-79.

Kloepffer, W. (2008). Life Cycle Sustainability Assessment of Products. *International Journal of LCA , 13* (2), 89-95.

Manderson, A. K. (2006). A system based framework to examine the multi-contextural application of the sustainability concept. *Environment, Development and Sustainability* , 85-97.

Martínez-Alier, J., Munda, G., & O'Neill, J. (1998). Weak comparability of values as a foundation for ecological economics. *Ecological Economics , 26*, 277-286.

Mauerhofer, V. (2008). 3-D Sustainability: An approach for priority setting in situation of conflicting interests towards a Sustainable Development. (Elsevier, Ed.) *Ecological Economics , 64*, 496-506.

McCarthy, T., Blackman, A., & Dickerson, J. (2001). War Over Arctic Oil. *Time , 157* (7).

Meadows, D. (1998). *Indicators and Information Systems for Sustainable Development: A report to the Balaton Group.* The Sustainability Institute. The Sustainability Institute.

Mendoza, G. A., & Prabhub, R. (2000). Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study. *Forest Ecology and Management , 131*, 107-126.

Mendoza, G., & Martins, H. (2006). Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecology and Management , 230*, 1-22.

Ministry of Housing, Spacial Planning and Environment. (2000). *Eco-Indicator 99 - Manual for Designers.* Ministry of Housing, Spacial Planning and Environment, The Hague.

Munda, G. (2000). *Conceptualising and Responding to Complexity.* Policy Research Brief, Environmental Valuation in Europe. Concerted Action funded by the European Commission DG-XII and co-ordinated by Cambridge Research for the Environment (CRE).

Munda, G. (2005). Measuring Sustainability. (Springer, Ed.) *Environment, Development and Sustainability , 7*, 117-134.

Neumayer, E. (2003). *Weak versus Strong Sustainability: Exploring the limits of two opposing paradigms.*

Norgaard, R. B. (1989). The Case for Methodological Pluralism. *Ecological Economics , 1*, 37-57.

Parris, T. M., & Kates, R. W. (2003). Characterizing and Measuring Sustainable Development. *Annual Review Environmental Resources , 28*, 13.1 -13.28.

Pearce, D. (1988). Economics, Equity and Sustainable Development. *Futures , 20* (6), 598-605.

Pearce, D. W., & Turner, R. K. (1990). *Economics of Natural Resources and the Environment.* Harvester Wheatsheaf.

Rawls, J. (1999). *A Theory of Justice: Revised Edition.* Harvard University Press.

Rees, W. E. (1992). "Ecological footprints and appropriated carrying capacity: what urban economics leaves out". *Environment and Urbanisation , 4* (2), 121-130.

Rockstrom_et.al. (2009). A safe operating space for humanity. *Nature* .

Saaty, T. L. (1990). How to Make a Decision: The Analytic Hierarchy Process. *European Journal of Operational Research , 48*, 9-26.

Saling_et.al. (2003). Eco-efficiency Analysis by BASF: The Method. *International Journal of LCA , 7* (4).

Schmidt, W.-P., & Sullivan, J. (2002). Weighting in Life Cycle Assessments in a Global Context. *International Journal of LCA , 7*, 5-10.

Singh, R. K., Murty, H., Gupta, S., & Dikshit, A. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators* , 189-212.

Solow, R. (1974). Intergenerational Equity and Exhaustible Resources. *The Review of Economic Studies , 41*, 29-45.

UN. (2005). *2005 World Summit Outcome. Resolution A/60/1.* United Nations General Assembly.

UN WCED. (1987). *Our Common Future: Report of the World Commission on Environment and Development.*

UNCED. (1992). *The Rio Declaration on Environment and Development.*

UNCSD. (2001). Indicators of Sustainable Development: Guidelines and Methodologies. *UN Commission on Sustainable Development* .

UNDP. (1990). *Human Development Report.* United Nations Development Programme.

UNEP-SETAC. (2009). *Guidelines for Social Life Cycle Assessment of Products.* United Nations Environmental Programme / Society of Environmental Toxicology and Chemistry.

United Nations. (2000). *Millenium Report: The Role of the United Nations in the 21st Century.* United Nations, United Nations Department of Public Information.

Wackernagel, M. (1994). *Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Towards Sustainability.* School of Community and Regional Planning. The University of British Columbia.

Wackernagel, M., & Rees, W. (1996). *Our Ecological Footprint: Reducing Human Impact on the Earth.* New Society Publishers.

WBCSD. (1996). *Eco-Efficiency and Cleaner Production: Charting the Course to Sustainability.* World Business Council for Sustainable Development.

World Commission on Environment and Development. (1987). *Our Common Future.*

Yoon, K. P., & Hwang, C.-L. (1995). *Multi-Attribute Decision Making: An Introduction.* Sage Publications, Inc.

Zamagni, A., Buttol, P., Buonamici, R., Masoni, P., Guinée, J., Huppes, G., et al. (2009). *Life Cycle Sustainability Analysis.* Coordination Action for Innovation in Life Cycle Analysis for Sustainability. CALCAS.

12 List of Tables

Table 5.1: PROSA-CALCAS comparison. Source: own elaboration. 22
Table 7.1: Different concepts of sustainability (Jabareen, 2008)..27
Table 7.2: Anthropocentric vs. ecocentric worldviews. Based on: (Pearce & Turner, 1990)......28
Table 7.3: Different forms of capital stock. 29
Table 7.4: Theories of intergenerational justice and operating principles (Gosseries, 2005)......30
Table 7.5: Parallelism along different disciplinary approaches 34
Table 7.6: Sustainability criteria for technologies 36
Table 8.1: Valuation methods and its limitations. Based on (Hanley, 1992)..............................40
Table 8.2: Weighting factors derived from critical environmental indicators (biodiversity and acidification included)..51
Table 8.3: Weighting factors derived from critical environmental indicators (logarithmic normalization). 51

13 List of Figures

Fig. 4.1: Research methodology – methodological steps 12
Fig. 5.1 Overview of PROSA's sequence of work. Source: www.prosa.org 14
Fig. 5.2: Spider graph for Integrated Sustainability Assessment of three product alternatives under PROSA 16
Fig. 5.3: LCSA framework proposed by CALCAS. Source: (Guinée, Huppes, Heijungs, & van der Voet, 2009) 18
Fig. 5.4: Left: ISO-LCA framework. Right: New LCSA framework proposed by CALCAS. Source: (Zamagni, et al., 2009) 19
Fig. 5.5: Separation of empirical knowledge, normative positions and transdisciplinary integration. Source: (Zamagni, et al., 2009) 20
Fig. 5.6: CALCAS conceptual framework for broadening the scope of ISO-LCA. Source: (Zamagni, et al., 2009) 21
Fig. 6.1 Left: Traditional three-dimensional view of SD. Right: (Heijungs_et.al, 2010) 23
Fig. 6.2: Proposed conceptual framework for the sustainability assessment of technologies 25
Fig. 7.1: The paradoxical balance underlying the concept of sustainable development 28
Fig. 8.1: From a concept of sustainability to indicators and indices (Boulanger, 2008) 39
Fig. 8.2: Three-dimensional view of Sustainable Development. Overlapping circles model. Source: (IUCN, 2006) 45
Fig. 8.3: Three-pillars of Sustainable Development. Embedded circles model. Source: (EEA, 1999) 46
Fig. 8.4: Environmental thresholds and their current situation according to Rockstrom et.al. 48
Fig. 8.5: Accumulated Damages (AD) approach. Scenarios 50
Fig. 8.6: Weighting factors based on linear and logarithmic normalization. 52
Fig. 10.1 Integration within relevant systems. 56
Fig. 10.2 Integration across relevant systems. 57

14 List of Equations

Eq. 5.1 Life-cycle sustainability assessment of products..14

Eq. 7.1: Kauffman's production function, where Y: aggregated income; E: environmental life support; A: level of technology (total factor productivity); K: manufactured capital; L: labour; α: output elasticity (assumed constant returns to scale)...36

Eq. 8.1: Relative damage calculation (criticality)..50

15 Appendices

15.1 Social Indicators for SLCA in PROSA

Employees	
Safe & healthy working conditions	National framework Number of fatal accidents at work Number of accidents at work Number of recognized occupational diseases and reports on elevated health risks Workplaces associated with noise, fumes, dust, heat, insufficient illumination Basic measures and arrangements to maintain and increase safety at work Measures and arrangements to maintain and increase health at work Access to clean drinking water and sanitary facilities at work Policies and programmes to combat HIV/AIDS and/or other locally important health issues (dengue, malaria, alcoholism etc.)
Freedom of association, right to collective bargaining & workers' participation	National framework Voluntary commitments by the company in the field of freedom of association & right to collective bargaining Reports on hindering workers' organizations and their activities Rate of unionization Possibilities for collective bargaining Possibilities for bottom-up communication
Equality of opportunity and treatment & fair interaction	National framework Voluntary commitments by the company in the field of equal opportunities and treatment Reports on discriminatory practices of the company Proportion of women in management positions Proportion of disabled employees Reports on harassment and mobbing Reports on sexual harassment Measures and programmes to maintain and increase equal opportunities and treatment
Abolition of forced labour	National framework Voluntary commitments by the company on abolition of forced labour Reports on cases of forced labour as defined by the ILO core labour standard conventions No. 29 and 105
Abolition of child labour	National framework Voluntary commitments by the company on abolition of child labour Reports on cases of child labour as defined by the ILO core labour standard conventions No. 138 and 182
Adequate remuneration	National framework Average remuneration level Average level of performance-related incentives Level of corporate minimum wages Ratio of corporate minimum wages to local costs of living Number of employees in the lowest remuneration segment Average level of performance-related incentives in the lowest remuneration segment Application of a transparent remuneration system Payment of wages in due time
Adequate working time	National framework Duration of one standard working week Maximum weekly working hours Duration of weekly rest period (at least 24 hours in one stretch) Duration of annual paid holidays Possibility for individually arranged working hours Fundamental decisions to increase / maintain / reduce working hours
Employment security	National framework Portions of permanent, non-permanent, freelance employees, and workers provided by temporary work agencies and sub-contractors Labour turnover rate Regulations on dismissal protection (cancellation period etc.) Fundamental decisions on hiring or dismissing employees
Social security	National framework Evidence of breaches of obligatory social contributions Duration and level of wage continuation in the case of illness Occupational pension schemes Maternity protection and childcare Additional occupational social contributions
Professional development	National framework Enhancement of professional qualifications on the job Proportion of employees covered by training programmes Average number of training days per employee Quality of training (participants' feedback) Language courses and integration measures for foreign employees
Job satisfaction	National framework Company festivities and social events Workplace reachability (location, public transport etc.) Aesthetic design of workplaces If necessary: Provision of housing facilities fit to live decently
Local and regional communities	
Safe & healthy living conditions	National framework Fatal accidents connected to the company's activities Accidents connected to the company's activities Negative and positive health impacts for the local population Noise, fume, dust, heat and wastewater emissions Measures and arrangements to maintain and improve safe and healthy living conditions
Respect of human rights	National framework Voluntary commitments by the company in the field of human rights Reports on human rights violations related to the company's activities Forced evictions / resettlements related to the company's activities Human rights training for employees, particularly for security staff
Respect of indigenous rights	National framework Reports on interference with social, economic or cultural activities of indigenous groups Evidence of exploiting indigenous knowledge

	and cultural heritage Reports on the violation of local traditions and values Respect of indigenous development goals Measures to maintain and improve the socioeconomic basis of indigenous groups
Community engagement	National framework Information possibilities for residents System to respond to community grievances Breaches of obligations established by local political and social decision-making authorities
Maintaining & improving social and economic opportunities	National framework Influence on local resource conflicts Provision / overburdening of infrastructure facilities Provision / overburdening of welfare services Additional education facilities for local residents Impact on local economic development
Society	
Public commitments to sustainability issues	National framework Awards for engagement in social and / or sustainability issues Membership in alliances and programmes to support and promote sustainable business practices Evidence of lobbying against implementing sustainability measures Publication of a sustainability report or social report
Prevention of unjustifiable risks	National framework Use of genetically engineered products and / or promotion of activities in the field of genetic engineering of living organisms, and in relation to patenting genes, organisms and plants Handling of radioactive substances and / or support of activities connected to nuclear power and warfare Evidence of other short-, medium- or long-term risks to human security
Employment creation	National framework Labour intensity (working hours per product or functional unit) / number of employees Development of indicators 1. and 2. within the last 3 years
Vocational training	National framework Number and proportion of apprentices (in relation to the total number of employees) Enhancement of professional qualifications on the job
Anti-corruption efforts & non-interference in sensitive political issues	National framework Evidence of corrupt and / or extortionate business practices Reports on improper involvement in political activities Corporate measures to combat corrupt business practices
Social & environmental minimum standards for suppliers and cooperation partners	National framework Proven efforts to implement social and environmental minimum standards at suppliers, sub-suppliers, intermediary dealers and cooperation partners Evidence of breaches of fundamental social and environmental minimum standards at suppliers, sub-suppliers and cooperation partners
Contribution to the national economy and stable economic development	National framework Contribution to GDP Direct investments Contribution to the foreign trade balance Development of innovative products and services The sector's stability during market crisis Evidence of competition distorting business practices (monopolisation etc.)
Contribution to the national budget	National framework Contribution to the national budget (taxes paid minus subsidies received) Evidence of tax evasion
Prevention & mitigation of armed conflicts	National framework Link between economic activities and armed conflicts
Transparent business information	National framework Comprehensive and transparent business reporting and sustainability reporting Handling of inquiries on sustainability issues
Protection of intellectual property rights	National framework Reports / court sentences on breaches of intellectual property rights
Users & Consumers	
Protection of the user's / consumer's health and safety	National framework Health opportunities / risks related to product use Accidents related to product use Fatalities related to product use Findings of product safety tests (incl. any awards, labels)
Quality of product or service	National framework Quality in relation to comparable products Good service, repairability, availability of spare parts Functioning procedure to settle consumer complaints Findings of product tests (incl. any awards, labels)
Fair competition & marketing practices	National framework Evidence of agreements and practices that distort competition Evidence of fraudulent, misleading or unfair marketing strategies Prevention of high downstream costs for maintenance and disposal Proportion of advertising costs in product price Evidence of infringements of commercial advertising law (reprimands by advertising monitoring council etc.) Evidence of dubious practices to bind consumers (non-compatible software, ink cartridges etc.)
Complete & understandable product information	National framework Precise and readily understandable information (user manual, constituent substances, safe use, maintenance, storage and disposal) as basis for information-based consumer decisions
Protection of user's / consumer's privacy	National framework Indications of infringements of consumers' privacy and/or data protection rights
Enhancing the user's / consumer's social and economic possibilities	National framework Reduction of consumer costs Suitability of product to meet needs of disadvantaged groups (disabled, aged, ethnic minorities etc.) General and widespread access to products and services

Source: Institute for Applied Ecology, 2007