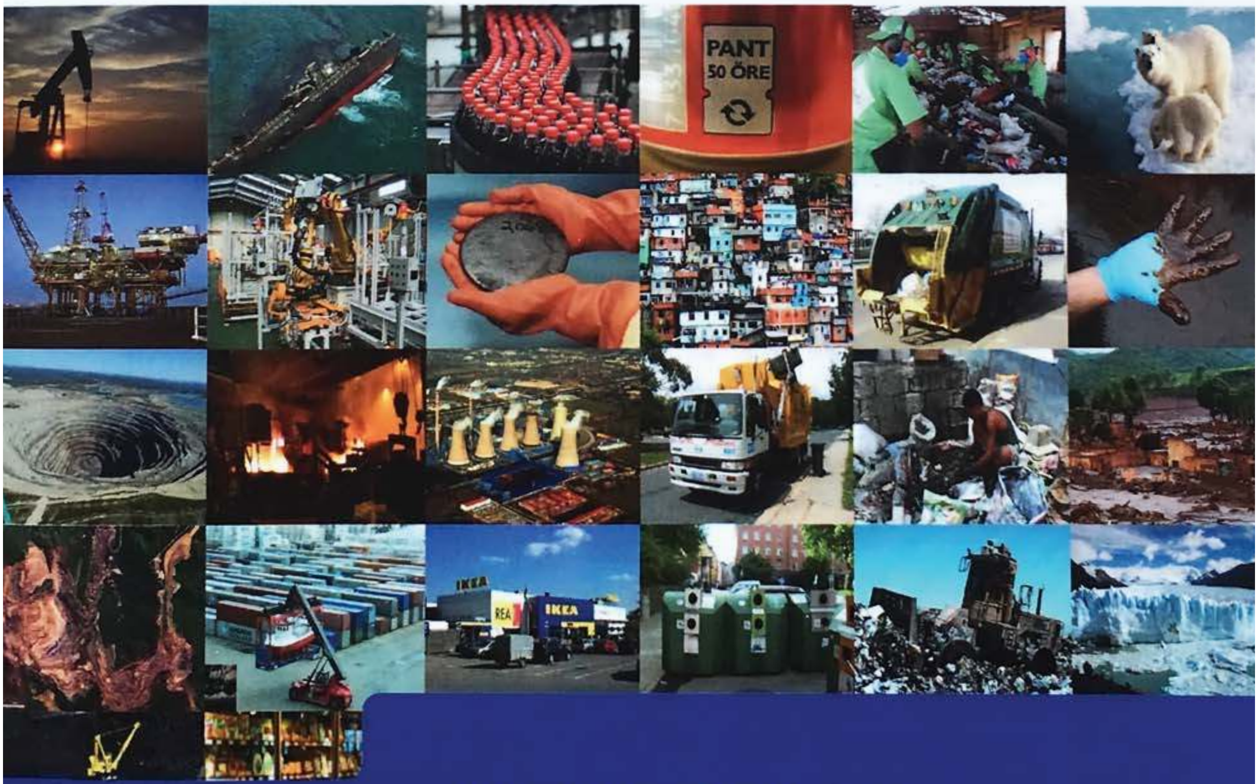
DOCTORAL THESIS IN INDUSTRIAL ECOLOGY
STOCKHOLM, SWEDEN 2016

Beyond Waste Management

Challenges to Sustainable Global Physical Resource Management

JAGDEEP SINGH



KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT

Beyond Waste Management

Challenges to Sustainable Global Physical Resource Management

Dedicated to

YOU

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Challenges to Sustainable Global Physical Resource Management

Doctoral Thesis in Industrial Ecology

Jagdeep Singh

Division of Industrial Ecology
Department of Sustainable Development, Environmental Science and Engineering
School of Architecture and the Built Environment
KTH Royal Institute of Technology Stockholm, Sweden

Beyond Waste Management: Challenges to Sustainable Global Physical Resource Management

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Table of Contents

Preface

While writing this preface, I started contemplating how I perceived PhD work when I started my research in 2010. After spending more than 5 years on this thesis, I am not sure I still have a clear answer. The classical PhD student knows 'a lot', but about a 'small' area, i.e. is an expert on a small issue. In my opinion, for problem-driven research, the opposite should be the case. Indeed, in the past few decades, the global sustainability challenges have occasioned a shift in scientific aspirations from basic research to 'relevant' or 'big science' to produce knowledge relevant to solve the problems of a system.

The main objective of this work was not apparent initially; various research questions guiding the work were progressively envisaged. Such an approach to PhD studies can be regarded as problem-based learning, which has its strengths and weaknesses. This can partly be attributed to the fact that when I started my PhD studies, my work was not tied to an existing research project with fixed deliverables and deadlines. I had the freedom and privilege to choose, shape and direct my studies according to my research interests. Furthermore, during my studies, I had the chance to work with other researchers from different educational backgrounds and with different expertise.

The research work was mainly carried out in a research group working in the area of sustainable production and consumption at the Division of Industrial Ecology, KTH Royal Institute of Technology. The group's research work comprised three PhD thesis projects (led by Rafael Laurenti, Rajib Sinha and myself), under the supervision of Björn Frostell, Professor of Industrial Ecology. These projects involved studying production and consumption in a systems perspective, but with a different focus. I studied production and consumption system from a sustainable waste management (WM) perspective, Rafael Laurenti from a sustainability-driven product design perspective and Rajib Sinha from a complex and dynamic systems modelling perspective to intervene in a complex world. The present thesis was greatly influenced by, and also influenced, the other two PhD projects.

I started my research journey with the WM systems analysis model ORWARE (ORganic WAste REsearch) developed jointly by the Division of Industrial Ecology at KTH, IVL Swedish Environmental Research Institute and SLU Swedish University of Agricultural Sciences. However, my original research plans were greatly re-shaped during the first six months of my PhD studies. I wanted to analyse various challenges to the WM system rather than analysing how waste, as received, can be managed in an environmentally and economically sustainable way. My research interests were further influenced after group interactions with Rafael Laurenti and Prof. Björn Frostell and I decided to study production and consumption systems from a WM perspective. My work diverged by viewing waste and resource issues as global issues rather than local/regional issues and was devoted to various social, technical, economic and environmental aspects concerning production, consumption and WM at a global level. The choice of this grand scale for conducting the research and for presenting and discussing the research findings was due to the nature of the research questions formulated.

This thesis is a continuation of my licentiate thesis in Industrial Ecology (2014), which analysed the global waste management system as part of a larger current design, production, consumption and waste management system and an even larger future physical resource management system. The present thesis extended this work, largely by providing more research content. The overall aim was knowledge integration to explore and understand the territory of resource management challenges in a holistic perspective. However, some compromises had to be made to discuss the complexities of sustainable global physical resource management at a global level – overlooking the details and quantitative analysis.

In my opinion, a PhD thesis is the start rather than the end of the research journey. My work to date was a platform where, apart from educating myself, I developed a valuable personal ethos towards global sustainability challenges. This prepared me for contributing to understanding and dealing with continually evolving global sustainability challenges. The thesis offers *'a way of thinking'* rather than *'pure knowledge'* about the global resource management system. I would like to end with a quote from one of the famous books of the 20th century that stressed the "importance of seeing known facts in a new light" and changed the whole outlook of the field of physics:

> *"The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science".*

In 'The Evolution of Physics' (1938) by Albert Einstein (1879-1955) and Leopold Infeld (1868-1968)

Sincerely,
Jagdeep Singh
28th March 2016
Stockholm, SWEDEN

PS: Each chapter in the thesis begins with a famous quote. These are not representative of the work in any sense and can be interpreted by the reader as they see fit. The research questions devised in this thesis are broad and therefore the contents are condensed and can be regarded as an independent piece of research. The appended papers provide more details of the results or how these were obtained.

My Debts

I wish to thank my supervisor Prof. Björn Frostell at the Division of Industrial Ecology for his encouragement and guidance throughout the project. I am also very thankful to Dr. Olga Kordas for her guidance and advice during the latter part of my PhD studies. I am indebted to Rafael Laurenti and Rajib Sinha for their wonderful friendship, kind support and great contributions in carrying out this research. I am also grateful to Isabel Ordoñez and Patrik Baard for sharing their experience, ideas and expertise during the collaboration. I am very grateful to Per Jacobsson for his valuable suggestions on improving previous versions of this thesis. I would like to thank my fellow PhD researchers Jiechen Wu, Graham Aid, Joseph Santhi Pechsiri, Jean-Baptiste Thomas, Hossein Shahrokni, Guanghong Zhou, Hongling Liu, Emma Risén, Kateryna Pereverza, Oleksii Pasichnyi and Mauricio Sodre Ribeiro for their chats and smiles in the corridor.

I would like to thank Åsa Svenfelt for enduring the role of advance reviewer for the thesis. I am indebted to Maria Malmström, Fredrik Gröndahl, Karin Orve and Kosta Walin for helping out during the official activities. I am thankful to other professors, researchers and staff at the Division of Industrial Ecology for creating a wonderful and cheerful atmosphere at the office. I would like to thank Erasmus Mundus Action 2 India4EU programme for the first three years of financial support. I would also like to acknowledge the Division of Industrial Ecology for financially supporting me in the last years of my PhD studies. The interpretations in this thesis remain my own and I am solely responsible for any errors.

Finally, I would like express my gratitude to my family and friends in India for their ongoing unconditional loving support.

Sincerely,

Jagdeep Singh
28th March 2016
Stockholm, SWEDEN

Abstract

Unprecedented global economic growth and rapid urbanisation have resulted in (over)exploitation of natural physical resources and release of large quantities of solid, liquid and gaseous wastes. This poses several global sustainability challenges due to natural resource scarcity and the diminishing carrying capacity of the planet to assimilate wastes. These challenges are exacerbated by the continuing growth in global population and the associated demand for physical resources to develop basic infrastructure to secure food security, eradicate poverty and improve health and education.

Current physical resource management was investigated in a global perspective in this thesis, in order to gain a deeper understanding of its implications in a sustainability perspective. In particular, the main challenges to the current physical resource management system and the kinds of systemic changes needed for sustainable physical resource management were examined.

In five separate studies, different theoretical and practical challenges to current physical resource management approaches were analysed. A descriptive literature review, causal loop diagrams and semi-structured interviews were performed to gather qualitative and quantitative inferences. Perspectives from industrial ecology, life cycle thinking, systems thinking and environmental philosophy were then applied to analyse global resource/waste management issues.

The analysis resulted in an overview of the global ecological sustainability challenges to current physical resource management and identification of major challenges to the global waste management system. Causal loop diagrams were used to qualitatively analyse the structure and behaviour of production and consumption systems responsible for unintended environmental consequences of purposive actions to improve material and energy efficiencies. Ways in which resource quality could be maintained throughout the system of production and consumption systems were determined by identifying challenges facing product designers while closing the material loops. A planning framework was devised to operationalise the sustainable development demands in society, including production and consumption systems.

A broader systems approach is proposed for future sustainable global physical resource management, focusing on ensuring societal functions within the human activity system. The approach involves designing and managing anthropogenic stocks of physical resources in order to reduce inflows of physical resources (to address resource depletion concerns) and outflows of wastes and emissions (to reduce environmental impacts). Life cycle-based databases linking resource consumption with waste generation are needed for improved global physical resource management.

Keywords: Sustainable global physical resource management, global waste management, systems thinking, life cycle thinking, planning framework, global environmental justice, circular economy

List of Appended Papers

Paper 1

Jagdeep Singh, Rafael Laurenti, Rajib Sinha, Björn Frostell (2014). Progress and challenges to the global waste management system. **Waste Management & Research** 32 (9), 800-812. doi:10.1177/0734242X14537868

Author's contribution to the paper:

I was responsible for planning the research, conducting the literature review and data collection and analysis. I organised the group-brainstorming sessions to analyse the findings of the research, wrote most of the paper and communicated during the journal's peer-review process.

Paper 2

Rafael Laurenti, **Jagdeep Singh**, Rajib Sinha, Josepha Potting, Björn Frostell, (2015). Unintended environmental consequences of improvement actions: A qualitative analysis of systems structure and behaviour. **Systems Research and Behavioral Science** (in press). doi: 10.1002/sres.2330

Author's contribution to the paper:

I took an active part in planning the research, literature review and data collection and analysis. I helped write most of the paper and revised the manuscript throughout the peer-review process. Rafael Laurenti organised the brainstorming activities and writing the paper and communicated during the journal's peer-review process.

Paper 3

Jagdeep Singh, Isabel Ordoñez (2015). Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy. ***Journal of Cleaner Production***. DOI: 10.1016/j.jclepro.2015.12.020

Author's contribution to the paper:

I was responsible for planning the research, the literature review and data analysis and wrote most of the paper. Semi-structured interviews during the study were conducted by Isabel Ordonez. Both authors took part in the peer-review process.

Paper 4 Rafael Laurenti, Rajib Sinha, **Jagdeep Singh**, Björn Frostell (2016). Towards addressing unintended environmental consequences: A planning framework. ***Sustainable Development*** *24 (1)* 1-17. doi:10.1002/sd.1601

Author's contribution to the paper:

I took an active part in planning the research, literature review and data collection and analysis. I helped revise early versions of the paper and participated throughout the peer-review process. Rafael Laurenti was responsible for organising the brainstorming activities, writing the paper and communicating during the journal's peer-review process.

Paper 5 **Jagdeep Singh**, Björn Frostell (2016). Towards a concerted approach to sustainable global physical resource management. *Manuscript*

Author's contribution to the paper:

I was responsible for planning the research, literature review and data collection and analysis. I also led the research and was responsible for writing most of the paper.

The appended papers are reprinted with the written permission of:

Other Related Research Papers not included in the Thesis

Paper A	Guanghong Zhou, **Jagdeep Singh**, Jiechen Wu, Rajib Sinha, Rafael Laurenti, Björn Frostell (2015). Evaluating low-carbon city initiatives from the DPSIR framework perspective. ***Habitat International*** 50, 289–299. doi:10.1016/j.habitatint.2015.09.001
Paper B	Rafael Laurenti, Rajib Sinha, **Jagdeep Singh**, Björn Frostell (2015). Some pervasive challenges to sustainability by design of electronic products – a conceptual discussion. ***Journal of Cleaner Production*** 108 (Part A). doi:10.1016/j.jclepro.2015.08.041
Paper C	Rajib Sinha, Rafael Laurenti, **Jagdeep Singh**, Björn Frostell, Maria Malmström (2016). Identifying ways of closing the metal flow loop in the global mobile phone product system: A system dynamics modelling approach *(under review)*. ***Resource, Conservation and Recycling***.

List of Figures

List of Tables

List of Abbreviations

CIT	Certified IPC Trainer
D	Designer
DPSIR	Driver-Pressure-State-Impact-Response
EU	European Union
WM	Waste Management
GDP	Gross Domestic Product
LCD	Liquid Crystal Display
LED	Light Emitting Diodes
ORWARE	ORganic WAste REsearch
PhD	Doctor of Philosophy
UNEP	United Nations Environment Programme
Wm	Manager of Waste Management

Definitions of the Important Terms

Human Activity System

The definition of the human activity system used in this thesis is inspired by Checkland (2000, p.115) "….. sets of human activities related to each other so that they can be viewed as a whole. Often the fact that they form an entity is emphasised by the existence of other systems (often designed systems) which are associated with them: the activities which make British Rail a human activity system, for example, are associated with designed physical system which is the railway network, with its stations, track, engine depots etc." Checkland (2000) argues that human activity systems are fundamentally different from natural systems in that they can be very different from one case to another (the observer can choose to view a set of activities as a system if he wishes to do so), whereas the natural systems without human intervention are the same. The term socio-economic system is also used in some cases. However, despite several definitions of that term, it can be confused with the formal economic system. Due to this lack of clarity, in this thesis the term 'human activity system' is used instead.

Physical Resources

Natural resources is a broad term and can encompass various physical and non-physical resources with subjective or intrinsic value for humans, such as material resources, energy resources and land resources, to name a few.

Inflows, Outflows and Stocks of Physical Resources

Inflows of physical resources refer to the extracted virgin physical resources entering the human activity system. Outflows refer to the negative environmental externalities of production and consumption systems within the human activity system, which include solid and liquid wastes and gaseous emissions. Stocks of physical resources refer to the long-term and short-term stocks of the resources in physical structures and products.

Wastes

According to the European Union Directives on Wastes (2008), "*waste is regarded as by-products or end products of the production and consumption processes respectively*". Thus, within the scope of the thesis, the term waste includes various solid, liquid and gaseous residues generated during production and consumption activities with or without economic significance. The terms 'waste' and 'resource' are used interchangeably here, to avoid any subjectivity in their meanings in the socio-economic system. However, due to the scope of Paper 2, the definition of waste used in that study is as given by UNEP, "substances or objects which are disposed or are intended to be disposed or are required to be disposed of by the provisions of national laws" (2007b).

Waste Management and Waste Management System

Waste management is a set of organised activities to avoid the generation of wastes, encourage reuse, repair and recycling and achieve end-of-life management of discards/wastes through energy recovery or landfill. The waste management system includes all the related systems for planning the activities and managing infrastructure for waste collection and treatment.

Complex/Complicated Systems

Complexity and complicatedness are synonyms in their dictionary meanings. However, in this thesis the *complexity* in systems arises due to the multitude of actors and their interactions within the systems that contribute to the system's non-linear behaviour, whereas the *complicatedness* emerges due to multiple systems interacting with the core system. Agent-based models are used to address the complexity due actor interactions and system-based theories to address the complicatedness of multiple system interactions.

Unintended Consequences

The unintended consequences are the outcomes of intended actions that: (1) May cause direct or indirect negative or undesirable effects from the perspective of an outsider; and (2) are not addressed by the actor of the actions. The unintended environmental consequences referred to in the thesis and in Papers 2 and 4 represent negative environmental externalities that are the outcomes of an economic/industrial activity on agents having no stake/say in the transaction involved. Therefore, the concept of unintended environmental consequences describes a negative impact on the environment by a purposive action, irrespective of whether it was intended or not.

Low-, Middle- and High-income Countries

Low-, middle- and high-income countries are defined here according to their per capita GDP given by the World Bank. The term middle-income countries includes both lower middle- and upper middle-income countries. However, the terms developing and developed countries are sometimes also used interchangeably. In such cases, the term developing countries includes both low- and middle-income countries.

Professional Designer

A person who is engaged in product development by profession. The product development process is the entire set of activities required to bring a new product concept to a state of market readiness (Otto & Wood 2001).

Systems Analysis

'Systems analysis' is used instead of 'system analysis' because the thesis aims to analyse different systems, rather than studying one system.

1. Introduction

"Every answer given on the principle of experience begets a fresh question."

[Immanuel Kant, 1724-1804]

1.1 Background

In the past few decades, unprecedented global economic growth and rapid urbanisation have been possible due to exploitation of natural resources. This has resulted in substantial improvements in well-being for large fractions of the world population. However, it has also resulted in increased resource extraction and release of large amounts of waste and emissions to the environment (Blanchard 1992; Gerbens-Leenes et al. 2010; Wenheng & Shuwen 2008). These large amounts of resource *inflows* to the human activity system and waste *outflows* from the human activity system (negative environmental externalities to production and consumption activities in the form of solid, liquid and gaseous emissions) have raised global sustainability concerns. On the one hand, the increased inflows of resources have given rise to resource scarcity and depletion concerns globally. On the other hand, the outflows of emissions have caused local/regional environmental problems (local/regional land, air and water pollution) and global environmental threats (global warming and climate change). These inflows and outflows are expected to rise further, since a large fraction of the world's population still needs access to physical resources to meet their basic demands, such as poverty eradication, achieving food security and ensuring healthy lives, as highlighted in the recent 2030 agenda for sustainable development (United Nations 2015).

Introduction

Due to increasing rates of resource extraction (and consumption), several resource scarcity urgencies have been highlighted since Hubbert (1956, p.21) first coined the term 'peak oil'. Concepts such as Factor 4, Factor 10 (Schmidt-Bleek, 2000; Weizsäcker, Lovins & Lovins, 1997), sustainable development space (Holden et al. 2014) and safe and just space (Dearing et al. 2014) highlight the radical reductions in material use needed to allow operationalisation of the concept of (ecological) sustainability. However, the geological and economic constraints to resource supply have so far been alleviated by finding alternative spatial territories or technological advances to explore scarce resources. Indeed, the scarcity of natural resources within local or regional boundaries has been an important catalyst for increased globalisation of production activities in the past few decades (cf. Evans 2010, p.5). Recently, a number of countries[1] have shown great interest in deep seabed exploration for polymetallic nodules, indicating promising economic prospects to exploit these resources due to increasing global metal demands. This indicates that, in the future, increasing economic costs of physical resources could lead to economic exploration of the seabed, the Polar Regions and deep forests such as the Amazon rainforests. These responses to resource scarcity appear to disregard the limits to growth and may pose severe sustainability risks in the future due to the (over)exploitation of several scarce resources.

Furthermore, isolated efforts to achieve physical resource management in the systems of production, consumption and waste management (WM) appear to be unaware of the above-mentioned resource scarcity concerns. These efforts have been strongly linked to, and dependent on, contemporary drivers, goals and implications and social, political, economic and environmental ambitions (Wilson 2007). Indeed, local/regional environmental problems guided the initial

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[1] Since 2001 when the seabed regime became operational, International Seabed Authority (ISA) has signed a number of contracts with entities and governments such as the China Ocean Mineral Resource Research and Development Association, Japan's Deep Ocean Resource Development, The Government of India, the government of the Republic of Korea, French Research Institute for Exploitation of the Sea, the Interoceanmetal Joint Organisation, the State Enterprise Yuzhmorgeologiya of the Russian Federation, the Federal Institute for Geosciences and Natural Resource of the Federal Republic of Germany. The existing contracts signed by ISA focus on research development activities and long-term environmental studies. More information at: https://www.isa.org.jm/sites/default/files/files/documents/isacontractors.pdf

development of WM systems (Wilson, Rodic, et al. 2012). Until the 1960s, waste management was limited to merely removing waste to prevent local health hazards (Wilson 2007). In the 1960s and 1970s, due to the environmental movements, waste disposal issues entered the political agenda in the developed countries. Furthermore, rising energy costs in 1980s led to the development of waste to energy technologies. In the 1990s, the emerging sustainability discussions recognised waste-related issues as a global rather than a local environmental problem. For the past two decades, WM has evolved with relatively broad aims to reduce waste generation and sustainably manage waste through approaches such as design for environment, cleaner production, industrial symbiosis, eco-industrial parks and extended producer responsibility. According to Wilson (2007), major drivers for progress in WM vary significantly throughout the world. Indeed, WM in several developing countries still relies mainly on open dumping/burning or sanitary landfills and the main driver is improving public health. Thus, the current WM regime predominantly focuses on reducing the impacts rather than preventing waste generation and suggests so-called 'end-of-pipe' solutions to waste problems rather than long-term sustainable measures (Jeffrey K. Seadon 2010).

Within industries, one of the major strategies to 'decouple' economic growth from environmental impacts has been to increase material and energy efficiencies. This has led to eco-innovations in the area of technology development, product design and production and consumption of consumer goods. However, these decoupling efforts have often rebounded owing to unforeseen responses to the initial interventions. This is mainly due to the unintended environmental consequences[2] of the improvement actions which are not addressed by the actor of the actions or are beyond the capacity of the actor to be addressed. Indeed, some recent studies (Vesilind et al. 2007; Vesilind et al. 2006) have indicated that companies' efforts

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[2] The term unintended environmental consequences in the thesis represents negative environmental externalities that are the outcomes of an economic/industrial activity on agents having no stake/say in the transaction involved, i.e. a negative impact on the environment by a purposive action, irrespective of whether it was intended or not.

towards sustainability are simply good business and morally neutral (neither good or bad).

The global community may anticipate that the efforts to increase material and energy efficiency and manage wastes could support the quest for sustainability to a limited extent. However, the significant reductions needed in overall resource consumption to address sustainability challenges to global physical resource management require planning and management at all levels in the globalised production and consumption chains. In addition, due to these globalised chains, the problem of sustainable physical resource management is fragmented from a strategic and institutional viewpoint. Therefore, actors cannot individually address the overall problem.

Current WM approaches in production and consumption systems implicitly accept that optimising WM efficiency ultimately contributes to the overall efficiency of the global production and consumption system. However, such an admission ignores the consumption levels, or in other words the rate at which waste is being generated. The current WM focus is summarised by O'Rourke et al. (1996, p.96) as:

"A team of design engineers may struggle for months over whether it is environmentally 'preferable' to use an aluminium or a plastic radiator-cap, while more fundamental questions about the sustainability of the gasoline-powered automobile are never raised."

Alternatively, technological and operational innovations have broadened the discussion on waste issues to achieve the required resource efficiency, yet they focus on the individual product or system in isolation rather than on a more coherent systems approach. In addition, the 'social embeddedness'[3] (Boons & Howard-Grenville 2011) in the context of social structures and processes responsible for enabling and/or constraining these approaches is largely ignored.

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[3] Boons & Howard-Grenville (2011) use the term 'social embeddedness' (social, cognitive, cultural, structural, political, spatial and temporal) in contextualisation of organisations' activities and decisions about material and energy flows and technical processes.

Despite the current efforts at waste management, waste reduction and resource management in production and consumption systems, resource *inflows* and waste *outflows* are still rising globally. The global community has therefore been confronting an intricate challenge to address these multiple sustainability concerns associated with current physical resource management. Broad ecological sustainability challenges to managing resource urgencies suggest a need for a transition from a linear to a circular economy where the *outflows* of wastes and emissions from human activity systems are largely minimised (see Figure 1). This suggests devising strategies to manage the anthropogenic stock of resources in a more sustainable way.

This thesis attempts to improve understanding of the (ecological) sustainability challenges facing current physical resource management practices. It departs from the current belief that WM in developed countries is sustainable, unlike that in developing countries, and investigates the systemic changes needed within the human activity system for sustainable physical resource management.

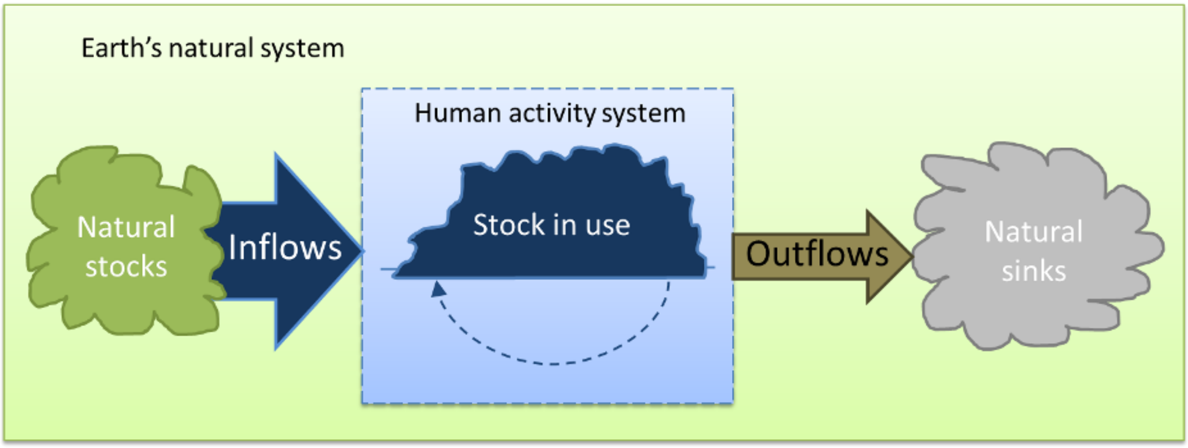

Figure 1. Illustration of inflows and outflows to the environment and anthropogenic stocks of materials in the current global human activity system. The growing demand for natural resources has increased the amounts of inflows and outflows and the stocks of the resources in use

1.2 Aim and Objectives of the Thesis

The main aim of this thesis was *to explore the (ecological) sustainability challenges facing the current approaches to physical resource management* in the systems of production, consumption and waste management and to identify the *necessary system transitions towards more sustainable global physical resource management*. The work is described in this cover essay and the five appended papers. The main objectives formulated to achieve the research aim were to:

1. Investigate the challenges facing current global waste management.

2. Identify and highlight the main limitations of current approaches to physical resource management.

3. Highlight necessary system transitions towards more sustainable global physical resource management.

1.3 Research Trajectory and Research Questions

In my Licentiate Thesis, the global waste management system is analysed as part of a large current design, production, consumption and waste management system and an even larger future physical resource management system. The research question examined was: *What is the current state-of-the-art of the global waste management system*? This resulted in work to study and analyse the global WM system as part of a physical resource management system with emphasis on design, production, consumption and WM. Progress and challenges to the global WM system were discussed to examine whether it is on a sustainable trajectory and where the bulk of the responsibility for waste issues lies. The Licentiate thesis concluded that developed countries have a high level of resource consumption, which to a great extent causes industrial waste generation in developing countries. This indicates that a broader view should be adopted on wastes[4] (solid, liquid and gaseous) by taking into account production, consumption and WM. Thus Paper 1

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[4] See Section 1.4 for the definition of wastes employed in this thesis.

started by discussing global WM issues and ended up on a resource management note. That is why from the second research objective onwards, the term physical resource management is used instead of WM.

Paper 1 provided a reference point for the subsequent research and forwarded a key massage that the realm of WM must be broadened beyond the traditional WM system to devise management strategies: (a) to avoid the generation of wastes at all and (b) to restore the waste resources to the socio-economic system. This in turn raised two broad research questions, which were addressed subsequent studies: (1) *What are the main challenges to current resource management approaches* and (2) *What kinds of system transitions are needed for sustainable global physical resource management?*

To guide the work within these broad questions, a view encompassing the sustainability issues associated with physical resources in a global perspective was essential. For this purpose, concepts from systems thinking, sustainability science, normative political theory and environmental philosophy were employed to conceptualise the global sustainable resource management challenges. Consequently, the subsequent objectives and research questions included a broader perspective than adopted in Paper 1.

Papers 2-5 contributed to the research objectives by identifying theoretical and practical *challenges* to various approaches to waste/resource management and discussing how these challenges could be addressed from a global sustainability perspective (see Table 1).

Many of the challenges to WM have root causes outside the WM system, e.g. the extricable link between waste generation and economic growth in the broader system of production and consumption. Paper 2 analysed how and why intended actions to improve environmental aspects within a system lead to unintended (negative) environmental and social consequences outside this system, i.e. an increase in negative environmental and social impacts (pollution, waste and economic inequalities) in other regions due to incremental improvements in material and energy efficiencies by an actor.

Some of the challenges to the global WM system identified in Paper 1 were further investigated in Paper 3. For this purpose, semi-structured interviews were conducted with designers and experts working with product development from post-consumer wastes (resources). These interviews provided important insights into the challenges facing product designers to close the material flow loops when products/systems are not designed for end-of-life recovery.

To incorporate the unintended environmental and social consequences in the planning process from an enterprise perspective, a planning framework was developed in Paper 4. The applicability of this framework was illustrated through the global mobile phone product system. The study concluded that 'product design and development' and 'the role of retailers and users in collection systems' are the central intervention points for addressing the unintended consequences.

Papers 1-4 predominantly examined WM issues (outflows) from a global ecological sustainability perspective. However, broad socio-economic aspects of the increasing inflows of physical resources into the human activity system were not fully explored in these papers. To address this gap, Paper 5 presented an overarching view of the physical resource management challenges in a global sustainability perspective by exploring the inflows and natural stocks of physical materials. This highlighted the need for global sustainable physical resource management which encompasses the broadest possible view on resources to holistically manage the inflows, stocks and outflows of physical resources in the human activity system.

Table 1. Contribution of Papers 1-5 to the objectives of the thesis

Thesis objective	Contribution of Papers 1-5 to this objective
To investigate the challenges facing current global waste management	• Examined and highlighted the major challenges facing current global waste management **(Paper 1)** • Investigated the practical challenges to closing post-consumer waste material loops **(Paper 3)**
To identify and highlight the main limitations to current approaches to physical resource management	• Explored and illustrated system structures and behaviours responsible for increased physical resource consumption and waste generation due to the unintended environmental consequences of environmental improvement actions in the system of production and consumption **(Paper 2)** • Highlighted the challenges to product/system designers in a circular economy **(Paper 3)** • Highlighted the need for broadening the system boundaries, explicitly accounting for causal mechanisms and feedback loops, and identifying responsibilities between stakeholders for sustainable physical resource management **(Paper 4)**
To highlight necessary system transitions towards more sustainable global physical resource management	• Proposed a broader systems approach to address various challenges to current global waste management **(Paper 1)** • Qualitatively illustrated system structures to reduce externalities while fostering the conditions needed for a transition towards a sustainable resource management **(Paper 2)** • Proposed a planning framework to devise resource management strategies in industries to alleviate their unintended environmental impacts **(Paper 4)** • Analysed and emphasised the challenges in planning sustainable physical resource management in a global context **(Paper 5)**

1.4 Scope

The definition of waste used in this thesis is that stated by the European Union Directive on Wastes (2008), *"waste is regarded as by-products or end products of the production and consumption processes respectively"*. Thus, within the scope of the thesis, the term waste includes various solid, liquid and gaseous residues generated during production and consumption activities with or without economic significance. Therefore, the terms waste' and 'resource' are used interchangeably in the thesis to avoid any subjectivity in their meanings in the socio-economic system. However, it should be noted that in Papers 1 and 3, the term 'waste' refers only to solid wastes, while in Papers 2 and 4 'waste' refers to solid, liquid and gaseous wastes. In Paper 5, the term 'outflows' refers to the solid, liquid and gaseous negative externalities to the production and consumption systems within the human activity system.

Natural resources entering the human activity system are either stored in the form of long-life structures or leave the human activity system as wastes and emissions. Natural resources is a broad term and can encompass various physical and non-physical resources with subjective or intrinsic value for humans, such as material resources, energy resources and land resources, to name a few. Within the scope of this thesis, the discussion is limited to the physical material resources needed for various production and consumption activities. The thesis is an earnest attempt to transcend the realm of current WM and move towards physical resource management.

1.5 Relevance

The global WM system was analysed here as part of a large design, production, consumption and waste system and also as part of an even larger physical resource management system. The role of current resource management practices in addressing global resource management problems was examined and future challenges to sustainable global resource management were discussed.

The thesis is primarily relevant for regional/national policy-making in the area of waste/resource management and can hopefully be of benefit to the WM sector –

including the WM industry and experts working with waste issues. The results could be used by consumer goods producers to address cooperate social responsibility issues throughout their value chains by: (1) identifying and addressing the unintended consequences of their business decisions and actions; and (2) planning for sustainable resource use - physical and non-physical resources, such as finance and humans - through a circular economy. This work could inspire product designers to incorporate broad sustainability challenges in their product design process. The overarching view on physical resources presented could be used to influence consumers towards environmentally-conscious consumer behaviour. Moreover, multiple perspectives on physical resource issues are presented and could be of great interest to students and researchers working with waste issues.

2. Theoretical Background and Delimitation of the Thesis

"Ignorance follows knowledge, not the other way around."
Stuart Firestein in his book 'Ignorance: How It Drives Science'.

2.1 System Scales and Levels of Analysis

The terms *'level'* and *'scale'* are understood differently among disciplines and scholars and used with interchangeable meanings. According to Gibson et al. (2000), a scale is a spatial, temporal, quantitative or analytical dimension used to measure and study any phenomenon, and a level is the unit of analysis located at different positions on a scale (see Table 2). Therefore, conceptually, scales could contain hierarchically ordered levels, but not all the levels are linked to one another in a hierarchical system (Gibson et al. 2000).

In today's globalised world, socio-economic activities cause intended and unintended social and environmental consequences at different levels along multiple scales. The driving forces or root causes of these activities and the consequences are often spatially and temporally distant along different levels. Furthermore, the regional, national and local administrative boundaries separate the institutional and management aspects of the human activity system. Failure to *completely* recognise the cross-level and cross-scale dynamics in the human activity system could cause unintended environmental impacts. Indeed, historically, human actions have resulted in unintended impacts, for example, collapsing fisheries, environmental problems and human-induced disease outbreaks (Millennium Ecosystem Assessment 2005).

Table 2 Different scales and levels of analysis. Based on the scope of the analysis, there can be other classifications of scales and more levels than mentioned in this table. Adapted from Gibson et al. (2000)

	Scales of Analysis					
	Spatial (Areas)	*Temporal (Rates, durations)*	*Jurisdictional (Administrations)*	*Institutional (Rules)*	*Management (Plans)*	*Network (Links)*
Levels	Globe	Annual	Inter-governmental	Constitutions	Plan	Trans-society
	Regions	Seasonal	National	Laws	Strategies	Society
	Landscape	Weekly	Provincial	Regulations	Projects	Neighbours
	Patches	Daily	Localities	Operating rules	Tasks	Family

Therefore, the scale at which an assessment is undertaken significantly influences the definition of the problem and the assessment results (Millennium Ecosystem Assessment 2005). Failure to acknowledge the driving forces at different scales can lead to unworkable and inequitable policies or programmes at all scales. Thus, before devising solution to a problem, an adequate understanding of the problem(s), associated driving forces and resulting impacts must be developed at a variety of levels (Ness et al. 2010).

In this thesis work, the global WM system was analysed as part of a broader system of physical resource management. Figure 2 illustrates different scales and levels of this global physical resource management system.

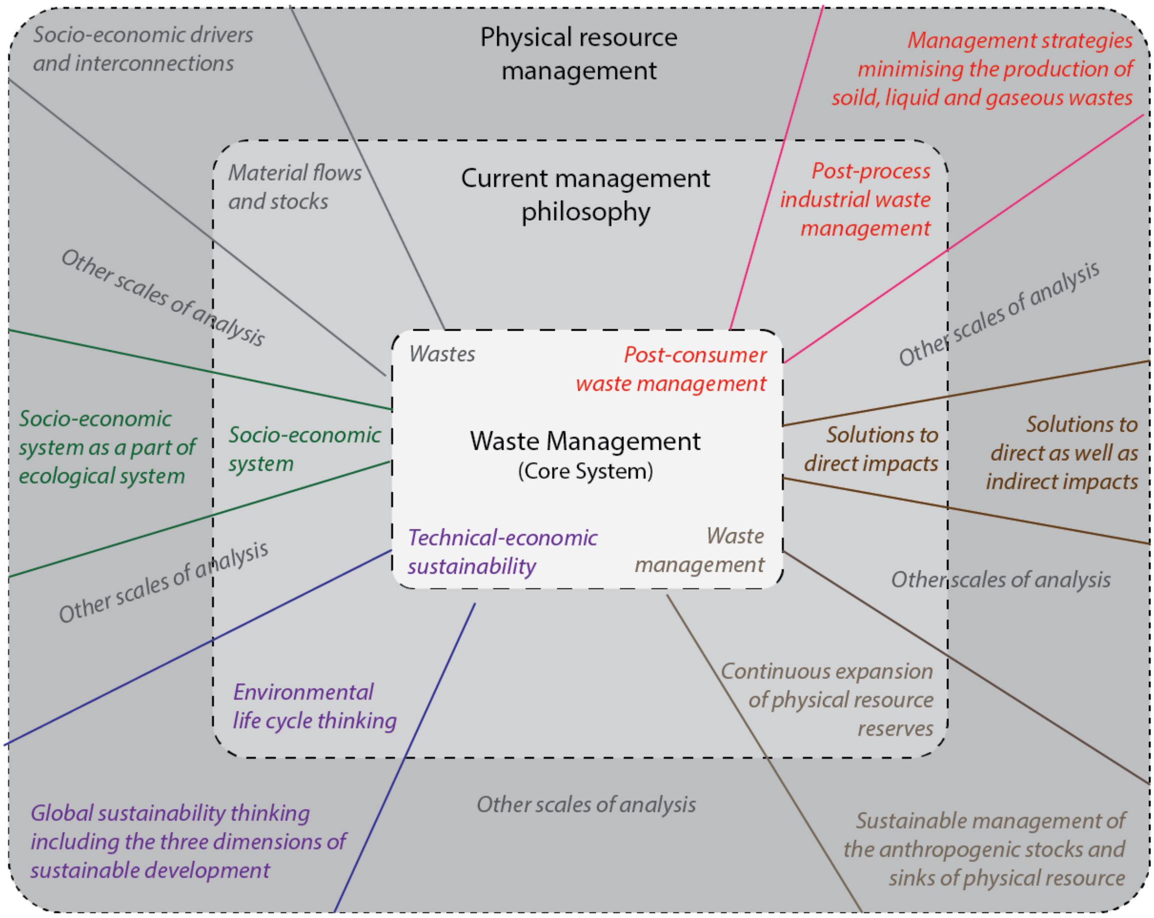

Figure 2. Illustration of different system scales and levels of the global physical resource management system, showing different divisions of the system. The colours represent the broader aspects of a particular scale.

2.2 Systems Thinking and Life Cycle Thinking

In a systems perspective, today’s globalised production and consumption systems are part of a larger, complex societal system. The raw materials (including the materials for energy production) required to operate production and consumption systems are sourced from different parts of the world, the products of these systems are distributed throughout the world and the waste materials are also managed through globalised WM chains. The activities within societal systems cause positive and negative impacts – social, economic and environmental – on both humans and the environment. These impacts, often spatially and temporally distant, are the direct or indirect outcome of these activities. Frostell (2013, p.837) argues that *“life cycle thinking is a strive to think in a more holistic way and consider a broader set of interactions between human activities and the global system, be they of* *physical, economic, or social character."* Therefore, from a life cycle perspective, instead of focusing on a specific part of a production and consumption chain, all the different phases in a combined production and consumption chain need to be recognised (Frostell 2013). In this sense, global sustainable physical resource management cannot be realised without adoption of a holistic view on global resource flows.

Systems thinking is a way of shifting the focus onto systems, rather than their parts, in order to define, frame and solve complex problems (Sweeney & Meadows 2010). Systems science intends to enhance understanding of the complexities of interactions between man and his environment in a holistic rather than reductive perspective (Skyttner 2005; Checkland 2000).

There are multiple manifestations of complex systems theory, summarised by Rotmans & Loorbach (2009, p.186) as: "*(1) formalized and computational modelling approaches, (2) a set of "understandings" of the behaviour of complex systems, (3) metaphorical use to describe social phenomena, and (4) philosophical considerations about the ontology and epistemology of complex systems"*. These manifestations could be viewed as part of the debate on 'hard' and 'soft' systems methodology. The main distinction between hard and soft systems methodology lies in the outlook on real world phenomenon. Hard systems thinking assumes that the world is a set of systems that can be engineered to reach easy-to-define goals and objectives and that performance can be measured quantitatively (Checkland 2000). Therefore, hard systems thinking is ideal for well-defined technical problems. Soft systems thinking views systems not as representations of the real world, but as intellectual devices, based on declared world-views, to explore problematic situations and desirable changes to them (Checkland 2000). Therefore, soft systems thinking is more of an organised learning system and is ideal for poorly defined, complex situations involving social and cultural considerations (Checkland 2000).

Both life cycle thinking and systems thinking (soft systems thinking) are utilised in Papers 1-5 to explore the various links between socio-technical systems – product design, production, consumption, WM, actor interactions – in order to develop a conceptual model of unintended environmental consequences of improvement actions and to propose a broader systems approach to sustainable global physical resource management.

2.3 Drivers-Pressure-State-Impact-Response (DPSIR) Framework

The DPSIR framework (European Environmental Agency, 1999) summarises the complex system interactions in the form of a linear causal chain. The framework serves as a heuristic device to facilitate engagement, communication and understanding between different stakeholders. The framework is a functional analysis scheme for structuring cause-effect relationships in connection with environmental and natural resource management problems. It is useful in describing the relationships between the origins and consequences of environmental problems and in understanding their dynamics through the links between DPSIR elements. In terms of this framework, socio-economic development and socio-cultural forces function as drivers (D) of human activities that increase or mitigate pressures (P) on the environment. Environmental pressures then change the state of the environment (S) and result in impacts (I) on human health, ecosystems and the economy. These may lead to societal responses (R) to the corresponding drivers, pressures, state of the environment or impacts via various mitigation, prevention or adaptation measures with regard to the environmental problems identified.

2.4 Industrial Ecology

Two of the earliest proponents of industrial ecology, Frosch & Gallopoulos (1990), highlighted the need for transformation of the traditional industrial systems of that time into a more integrated model – an industrial ecosystem – to minimise the use of energy and material and waste generation. Industrial Ecology was viewed as "*a better system for the coordination of technology, industrial processes, and consumer behaviour*" (Frosch & Gallopoulos 1992, p.290). Later, Graedel and Allenby (1995, p.9) affirmed that "*industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution*." The perspectives of industrial ecology were viewed as "*new thinking*" (Socolow et al. 1996).

The scope and definitions of industrial ecology are not yet completely fixed, but according to Thomas et al. (2003, p.1) "*the new field of industrial ecology focuses on reducing the environmental impacts of goods and services, on systems-based analysis of environmental problems, and on innovations that can significantly improve environmental performance*". Furthermore, Boons & Howard-Grenville define industrial ecology as "*the study of the material and energy flows resulting from human activities. This study provides the basis for developing approaches to close cycles in such a way that ecological impacts of these activities are minimised*" (2011, p.13).

These emerging definitions of the field of industrial ecology possess a common attribute – a focus on material and energy flows. Allenby (2009) argues that this focus is of limited relevance amid the emerging complexities in the real world and that the integrated cluster of technology that is rapidly redefining our world provides the scientific and technological basis for obsolescing many of the assumptions of industrial ecology. He also raised the issue that industrial ecology must learn to include radically increasing complexity of at least four kinds: static, dynamic, wicked and scale. Static complexity arises due to the number of parts and their linkages. Dynamic complexity arises from new and unanticipated ways of interactions and constantly changing emergent behaviours and network configurations. Wicked complexity arises from psychological and social dimensions of the anthropogenic world and its integrated human/natural/build systems. Scale complexity arises due to the fact that humans have impacts not just on local environments, but also on the global framework of physical, chemical and biological systems, but there is no discipline or intellectual framework comprehending the complexity at that scale. Furthermore, Allenby (2009) argues that the understanding of the complex systems comprising these complexity types is conditioned by the chosen system boundaries, which are in turn decided by the purpose of the enquiry. Some of these complexities have been highlighted in a recently published work by Boons & Howard-Grenville (2011) entitled '*The Social Embeddedness of Industrial Ecology*'.

System analysis tools have been expanded from simple static mathematical models to more sophisticated tools such as system dynamics and agent-based models. Yet these models fail to grasp all the real-world complexity and complicatedness, e.g. Andersson et al. (2014) argue that the narrative/qualitative approaches theorising about wicked systems have some advantages over the mainstream complexity science predominantly based on reductionist ideals, as these approaches can handle the heterogeneity, contingency and multilevel nature of wicked systems.

A special feature of the Journal of Industrial Ecology focusing on visions for industrial ecology and presenting key directions for the development of that field, particularly the role of eco-efficiency, raised several issues needing attention in the field: impact- or burden-shifting; inter-resource dynamics; more collaborative research between industrial ecology and social sciences such as innovation research, institutional analysis and international relations; major shifts in consumption patterns, sustainable de-growth; conceptual duality and lack of a normative framework for industrial ecology (Huppes & Ishikawa 2011b).

In conclusion, the new field of industrial ecology has plenty of room for improvement. This thesis presents a new way of thinking, largely inspired by the concepts and criticisms of the field of industrial ecology, that involves broadening the system boundaries of current WM to include the upstream systems of production and consumption in order to devise physical resource management strategies.

2.5 Environmental Philosophy

Environmental philosophy is a branch of philosophy that focuses on normative aspects of human-nature interactions. In this thesis, various concepts or principles from environmental philosophy are employed to conceptualise the problem of sustainable global physical resource management. These include normative concepts such as rights and fundamental interests, justice and responsibility. Several of these principles are often discussed in the field of climate justice (Shue 2014; Caney 2005; Moellendorf 2014). However, those discussions are primarily limited to discussing one resource – the atmosphere's capacity to absorb greenhouse gases. In this thesis, these principles are discussed in relation to fair access to natural resources globally.

Normative concepts such as 'rights' and 'fundamental interests' play a role in identifying what would constitute fair access to a resource. Rights, in this sense, refers to protecting fundamental interests (such as right to life, health, subsistence, etc.) (cf. Caney 2005, p.767; Raz 1986). If an individual has the right to subsistence and a certain amount of a specific resource is required to protect that right, it is permissible for the individual to consume a specific level of that resource. However, the individual is not entitled to consume beyond what exceeds the protection of those fundamental interests, since it could deprive others of their fair share.

According to the philosopher Dale Jamieson (2010), moral responsibility often requires causal efficiency as a necessary condition. However, for issues with such grand scales as global resource management, the causal influence is not always so manageable or identifiable, due to the involvement of many actors and extended time frames (see Jamieson, 2010; van de Poel, Nihlén Fahlquist, Doorn, Zwart, & Royakkers, 2012) for a discussion on moral responsibility and the problem of many hands). Therefore, it becomes necessary to understand and attribute responsibility not only for risks, but also for managing such risks at a global level.

These perspectives from environmental philosophy are often discussed in the arena of climate justice and used to address questions regarding responsibility, rights, governance of the environmental problems concerning climate change mitigation and adaptation. The thesis discusses these perspectives in relation to the proposed sustainable global physical resource management discussed in Paper 5, where they are used to position the results of Paper 5 in a global context.

2.6 Sustainability and Sustainable Development

The term sustainability '*supposedly*' defines the state of affairs necessary for the well-being of humanity in harmony with the ecological system. The concept of sustainable development proposes pathways for human development in order to reach this state of affairs. This thesis adopts a similar view of sustainable development as given in the Brundtland Commission's report – "*sustainable development is development that meets the needs of the present without compromising the* *ability of future generations to meet their own needs*" (1987, p.16). Natural physical resources provide raw materials for the production of goods and services and are fundamental to every economy. Wastes and emissions generated during production and consumption activities cause adverse environmental, economic and social impacts, and are directly linked to the issue of resource scarcity. Furthermore, these issues are related to equity and justice at a global level due to the mere fact that humanity has a vital challenge ahead to support *a growing world on a small planet*.

Sustainability has been regarded as a vague and politicised term (Lant 2004) in its variety of meanings in different contexts (Graedel & Klee 2002). Rapidly increasing awareness of the importance of the concept of sustainability has resulted in a myriad of terms explaining the concept (Glavič & Lukman 2007). However, the basic principles in achieving sustainability remain environmental/ecological, economic and societal in nature. Within the scope of the present thesis, various environmental principles such as resource scarcity; ecological principles such as industrial ecology (Frosch & Gallopoulos 1992) and sustainable production and consumption systems (United Nations Environment Programme 2010); and societal principles such as social responsibility[5] (Glavič & Lukman 2007) act as the guiding principles.

Kates et al. argue that *"a new field of sustainability science is emerging that seeks to understand the fundamental character of interactions between nature and society"*. This new field integrates industrial, social and environmental processes in a global context (Mihelcic et al. 2003). Sustainability science proposes that science must focus on the character of nature-society interactions; relate to our ability to guide those interactions along a sustainable trajectory and ways to promote social learning to navigate the transition to sustainability; and be connected to global political agendas (Kates et al. 2001). Such problem-solving efforts may require an

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[5] According to Glavič and Lukman (2007, p.1879), social responsibility "*refers to safe, respectful, liberal, equitable and equal human development, contributing to humanity and the environment*."

approach different from the traditional research strategies. As described by Weinstein & Turner (2012, p.viii):

"[]………Any solution to the emerging conflicts arising on the path of long-term sustainability will, in part, require the integration of the biophysical and social sciences into a new transdisciplinary science referred to as "sustainability science", continued development and refinement of a number of new approaches and concepts including a systems approach to problem-solving, social learning, resolution of the "paradox of the dual mandate" and enhanced incorporation of human dimensions into resource management……..[]"

Kates et al. (2001) summarised such strategies as:

- *Covering the range of spatial scales between diverse phenomena*
- *Accounting for temporal inertia and urgency of processes*
- *Dealing with functional complexity resulting from multiple stresses*
- *Recognition of a wide range of outlooks equating to usable knowledge in both science and society.*

In this thesis work, these sustainability science principles and strategies were utilised to design a research heuristic to develop a broader systems approach to sustainable physical resource management. In relation to physical resource management, the definition of the concept of sustainability used was as a '*state of affairs*' ensuring availability and accessibility of natural resources for present and future generations globally to meet their basic subsistence level. This *state of affairs* includes not only the practices of sustainable waste/resource management, but also a social agenda from the individual to global level. However, the thesis predominantly presents ecological sustainability perspectives of sustainable global physical resource management.

3. Methodology

"It is very difficult to find a black cat in a dark room, especially when there is no cat."
An old proverb by anonymous

This section describes the research approach, research design and research methods/tools employed in the thesis. The problem under investigation was approached using soft systems thinking (Checkland 2000) and the DPSIR framework to address the main drivers of the problem. Both quantitative and qualitative inferences were applied and therefore the research design included a mix of methods/tools within three main logical structures of research: critical interpretive synthesis (Dixon-Woods et al. 2006), group model building (Vennix 1996) and case study. Within these research structures, the main methods/tools used were: literature study, causal loop diagrams, semi-structured interviews and a product study.

3.1 Research Approach

In this research, the problem of waste/resource management was viewed as a post-normal problem, which has been described as a complex problem where facts are uncertain, values in dispute, stakes are high and decisions are urgent (Funtowicz & Ravetz 1994). In these problems, an intricate pattern of complexity emerges due to the interactions of multiple systems and a multitude of actors. To understand this complexity, broad research questions were devised.

In order to address these broad research questions, the systems boundaries of the WM system were expanded to allow inclusion of radical ideas and novel possibilities. Soft systems thinking proved to be very useful in placing the WM system in the context of large production and consumption systems and the even larger global physical resource management system, to explore the drivers of the problems and devising proactive strategies addressing the problems. To operationalise this thinking and map the interactions between the human activity system and the natural systems, the DPSIR framework was utilised. Here, the human activity system represented the socio-technical and economic systems associated with production and consumption activities. The natural systems consisted of the ecosystems, environmental systems and natural physical resource systems.

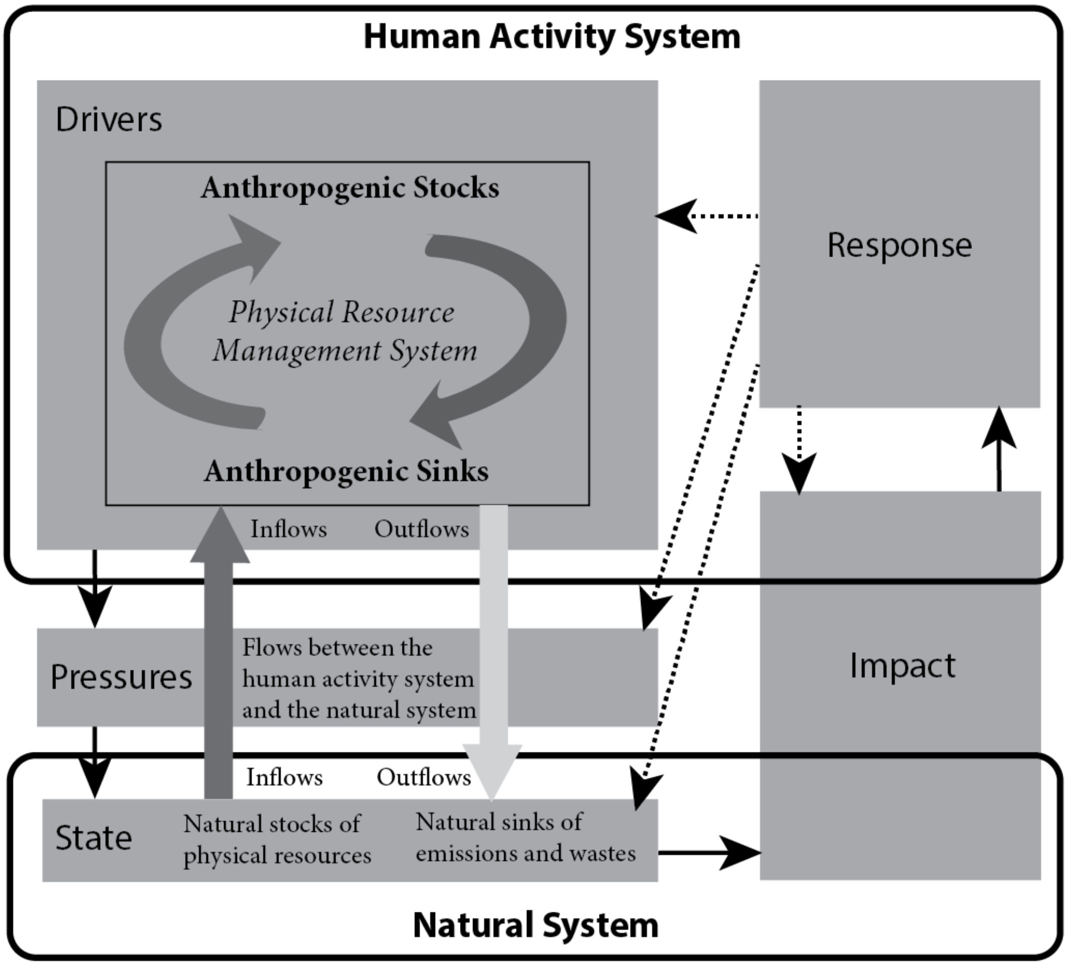

Figure 3. Illustration of the interaction between the human activity system and the natural system within the DPSIR framework. The dotted arrows represent the responses within the human activity system to address: the main drivers of the problem, the resulting pressures, the degrading state of the environment, and adverse impacts of the problem on the natural system and the human activity system. The increasing inflows of physical resources and the outflows of emissions and wastes are framed as the main pressures in the thesis

Figure 3 illustrates the interactions between these systems within the DPSIR framework. The *drivers* represent the activities within the human activity systems that lead to *pressures*[6] such as increased inflows of physical natural resources (raw material extraction) from the natural system and increased outflows of emissions and wastes to the natural system. The *state* represents the quality of the natural system that can have *impacts* on both the human activity system and natural systems. The *responses* are the actions initiated in the human activity system to manage or mitigate these impacts. In mainstream WM-related research, the impacts percieved on the human activity system and natural systems predominantly guide the responses taken in the DPSI phases. Therefore, the responses devised focus mainly on efficient management of the wastes/emissions generated, in order to reduce the negative envirowmental, social and economic impacts. Thus they focus less on developing prevention strategies for limiting/reducing the pressures (inflows and outflows). The *drivers* of the problem are identified and highlighted by understanding the global physical resource management system in society.

The thesis aspires towards the old notion '*think globally, act locally*' by highlighting the need for devising management strategies within WM that not only address the local context of sustainability (waste/pollution problems), but also conform to the global context of sustainable physical resource management (such as resource scarcity and depletion and ensuring fair access to resources to current and future individuals requiring resources). This forms the overall context of the thesis (see Figure 4).

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[6] The pressures represent the flows between the human activity system and natural systems, for instance natural physical resources and emissions and wastes.

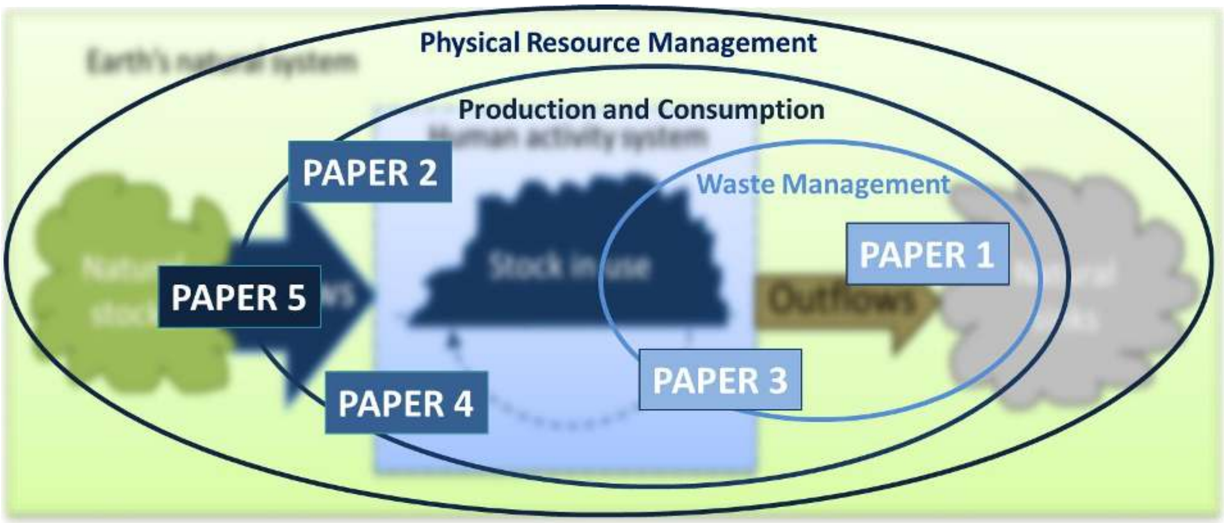

Figure 4. Illustration of the overall context of the thesis and the appended papers in relation to the system illustrated in Figure 1. Papers 1 and 3 focus on the outflows of solid wastes and issues linked to their sustainable management; Paper 2 analyses management aspects of the material stocks in the production and consumption; Paper 4 proposes a planning framework as an interface between sustainable development demands and the interventions (improvement actions) to respond to the sustainability challenges within the socio-economic system; and Paper 5 explores the sustainability aspects of the natural stocks and the inflows of physical resources

3.2 Research Design

To understand the complexity of the global physical resource management system, a highly inter-disciplinary discourse was carried out by expanding the systems boundaries. For this purpose, literature on waste/resource management aspects was studied and synthesised: (1) to understand how the complex issue of resource management is currently perceived (pragmatic reasons); and (2) to question, in a systematic way, how sustainable global physical resource management ought to be shaped. In this regard, the thesis highlights the role of social systems in shaping global physical resource management. Therefore, it includes a significant amount of qualitative inferences. A predominantly qualitative focus allowed inclusion of diverse perspectives that would otherwise have been difficult due to the imposed constraint of system boundaries.

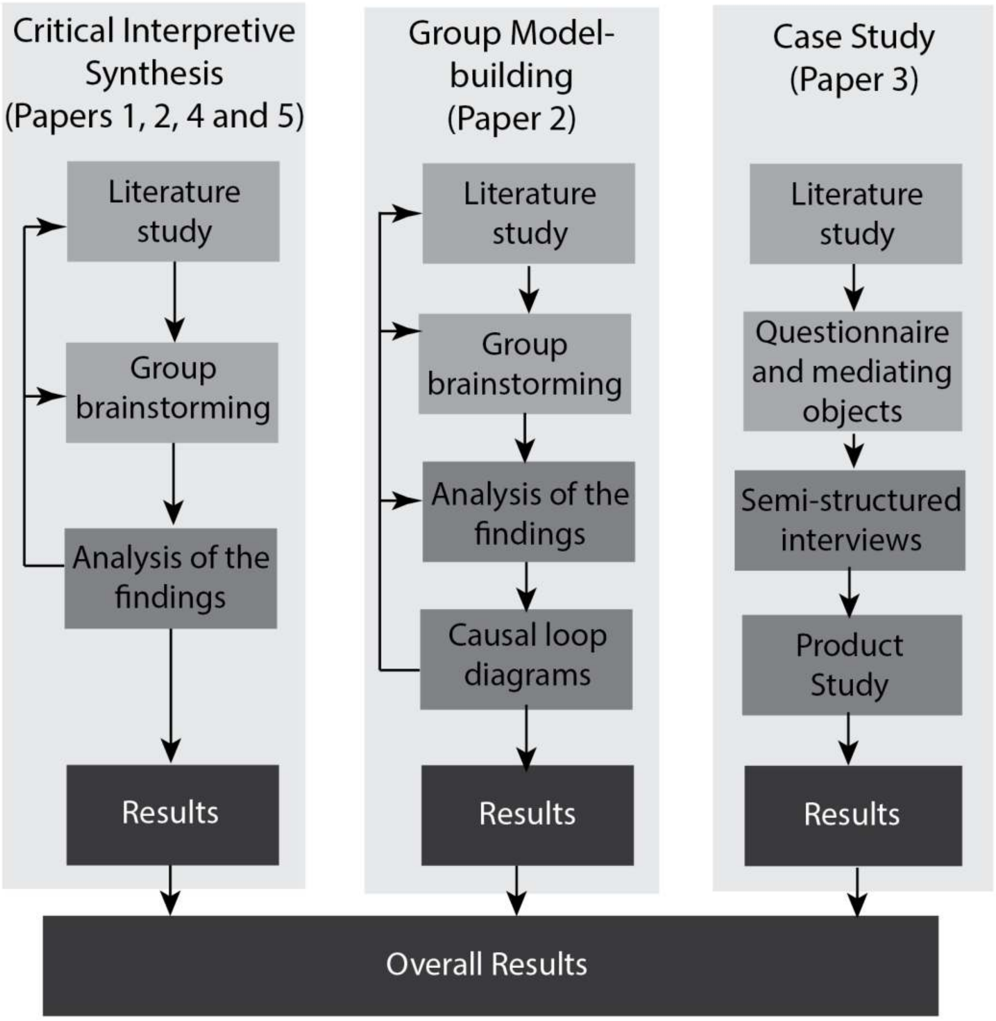

Figure 5. Three main structures of research enquiry used in the thesis. The critical interpretive synthesis involved group brainstorming sessions to analyse the results. Group model building also used group brainstorming sessions to develop the causal loop diagrams. Within the case study, a questionnaire and mediating objects were used to guide the semi-structured interviews. These interviews provided product examples along with the challenges faced during the development of these products. Similar examples of the products developed from post-consumer waste were collected and analysed further

Critical interpretive synthesis (Dixon-Woods et al. 2006), an approach to synthesis of multidisciplinary and multi-method evidence, was utilised to analyse the literature. This approach is different from the traditional literature review in the sense that the review questions are not precisely specified at the outset of the study, but rather iteratively revised during the literature review and analysis process (Dixon-Woods et al. 2006). Therefore, critical interpretive synthesis involves an iterative approach to refine the research questions and search and select the literature. This iterative approach enables the scientific enquiry to cross disciplinary boundaries of fields. The critical interpretive synthesis explicitly allows the integration of qualitative and quantitative evidence during the interpretive process (Dixon-Woods et al. 2006). In this thesis, the interpretive process involved the study and synthesis of the literature on specific research topics in a group (see Appendix 1). Descriptive synthesis is interpretation of the findings based on the reviewers' experience and the quality and content of the available literature (Fink 2010). For this purpose, group brainstorming[7] (Osborn 1963) sessions were carried out by co-authors[8] of the papers. The literature synthesis process was carried out in an iterative way to allow inclusion of diverse perspectives and theories from different disciplines. The extended literature synthesis was carried out to develop Papers 1, 2, 4 and 5 (Figure 5).

Paper 2 also utilised the group model-building (Vennix 1996) approach, in that case based on the system dynamics methodology. The group model-building method is often used during the initial stages of a system dynamics model development to *qualitatively* identify the problem and conceptualise the system (Vennix 1996). In Paper 2 the group model-building method was utilised in a slightly different way, where the problem identification and conceptualising phases of the system dynamics methodology formed the basis for suggesting strategies to address the problem under investigation. A literature study and group-brainstorming sessions were utilised to develop the causal loop diagrams.

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[7] The term brainstorming (Osborn 1963) was popularised in the 1953 book *Applied Imagination.* It is a group or individual creativity technique by which efforts are made to find a conclusion for a specific problem by gathering a list of ideas spontaneously contributed by its member(s). In this thesis it was used in a slightly different way. Instead of gathering spontaneous ideas, a literature review was carried out and the important findings were discussed by research group members.

[8] Apart from the author, group members included Björn Frostell, Rafael Laurenti and Rajib Sinha of the Division of Industrial Ecology (Papers 1, 3, 4 and 5), Isabel Ordonez of the Division of Design and Human Factors, Chalmers University of Technology (Paper II), and Patrik Baard of the Department of Philosophy and History of Technology (Paper V), KTH. Björn Frostell is Professor in Industrial Ecology with special interest in systems analysis and an expert in the field of life cycle thinking and systems thinking. Rafael Laurenti is conducting research in the field of unintended environmental consequences of improvement actions and is a PhD student at the Division of Industrial Ecology. Rajib Sinha is doing his PhD research in the field of household metabolism. Patrik Baard is pursuing a PhD in the area of setting sustainable long-term goals. Isabel Ordonez is a PhD student conducting her research in the area of product development from wasted resources. This research group contributed diverse perspectives on waste/resource issues during the brainstorming sessions.

Causal loop diagrams ware then used as the first step to evaluate the problem of waste generation and devise qualitative response strategies.

Papers 1 and 2 identified the WM system as one of the key elements in the global physical resource management system. Therefore in Paper 3 the system boundaries were restricted to studying post-consumer wastes and a case study was designed to investigate the practical challenges to closing the post-consumer (waste) material loops. For this purpose, semi-structured interviews were carried out using two mediating objects. Engelbrektsson (2004) describes a mediating object as something that stimulates discussion, enhances users' understanding of a product or product concept and/or simplifies the dialogue between users and the developer. The product examples collected during the interviews were then further analysed, which provided some useful insights on the upcoming circular economy. Based on the analysis in Papers 1-3, a planning framework was developed in Paper 4. This framework became the point of departure for Paper 5, which examined how to approach sustainable global physical resource management.

3.3 Research Methods/Tools

This section describes how various research methods and tools were utilised in Papers 1-5 (see Table 3).

Table 3. Research methods used in Papers 1-5

Research Method/s	**Paper**				
	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5
Literature study and analysis and evaluation of the findings	X	X	X	X	X
Causal loop diagrams		X			
Semi-structured interviews and product study			X		

3.3.1 Literature Study and Analysis and Evaluation of the Findings

A detailed literature review was conducted in all of Papers 1-5 and comprised collecting, analysing, evaluating and summarising research material on a specific topic (Fink 2010). The aim was to describe current knowledge about the research topic and support the need for and significance of new research.

The literature review process conducted for Paper 1 was based on literature on progress in WM activities throughout the production, consumption and waste system and challenges to the global WM system. The outcomes of the literature survey, followed by the brainstorming sessions, provided a deeper understanding of waste issues in a global perspective and acted as the basis for the proposed broader systems approach to WM and its aims. The main research questions guiding the literature review were: *What measures are employed in production, consumption and WM systems for waste prevention and treatment; and What are the major challenges facing the global WM system?* The findings from the literature review were further analysed and evaluated during the group brainstorming sessions in order to contextualise them in a global perspective. The main research question pursued during these sessions was: *What do progress and the challenges involve in a global perspective?* Furthermore, quantitative data on global waste generation and management were collected and analysed to determine: *Shortcomings in the current 'rather isolated' efforts at waste prevention and treatment in the production and consumption system as regards managing the physical resources in society in a life-cycle thinking perspective*. For the major challenges facing global WM, a broader systems approach to resource management addressing these challenges was proposed as the foundation for subsequent research.

Papers 2 and 4 involved literature reviews on (i) the current economic growth paradigm, (ii) consumption rebound effects; and (iii) negative externalities to the industrial approaches to improve energy and material efficiencies. This resulted in an understanding of: *How these issues relate to each other in a broader system of production and consumption; how negative environmental externalities arise as a result of undervalued natural capital and increased waste and pollution;* and *how negative social impacts arise due to economic inequalities.*

In Paper 3, the main aim was to examine resource circulation in practice and highlight opportunities and challenges to the upcoming circular economy. Therefore, the literature survey involved understanding resource recovery routes as defined in theory, especially in the EU waste hierarchy and the circular economy proposed by the Ellen MacArthur Foundation (2012; 2014). It also involved analysing information on practical examples of different products developed from post-consumer materials through websites, reports and semi-structured interviews (explained in Section 3.3.3). The literature review resulted in an understanding of the flow patterns of post-consumer materials and resource recovery routes in theory.

The literature review in Paper 5 focused on studying and analysing the broad sustainability challenges to current global physical resource management. The specific study topics included: documents on 'peak' extraction rates of various key natural physical resources such as fossil fuels, phosphorus, water and critical material inputs for industrial production (see Appendix 3); the drivers for the increasing global resource metabolic trends and their broad sustainability constraints. The focus was on the issue of resource scarcity in order to understand: (1) how these urgencies have so far been perceived by the global society; and (2) the sustainability challenges facing global society due to these multiple resource scarcities. Quantitative data on global resource reserves and annual production rate were collected and analysed. The literature survey provided an overarching view of the sustainability challenges facing current global physical resource management. The quantitative data on global resource reserves and annual production rates were used to evaluate *longevity estimates*[9]. The main research questions pursued during the group brainstorming sessions to analyse the results from the literature review and data synthesis were: *How critical are these physical resources in a resource-supply perspective; how are these resource urgencies perceived so far;* and *what are their implications in a global context?*

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[9] $\text{Longevity (years)} = \frac{\text{The resource reserve for year n (tons)}}{\text{The production rate for year n}-1\text{ (tons} \times \text{year}^{-1}\text{)}}$

3.3.2 Causal Loop Diagram

In a causal loop diagram, various feedback structures of systems are represented through arrows and polarities (Sterman 2000). The arrows denote the causal link between two variables and the polarity indicates the dependency of a variable on the independent variable. A positive ("+") sign means that both variables change in the same direction, i.e. if one increases, the other increases and vice versa. With a negative ("-") sign, the variables change in the opposite direction; if one increases, the other decreases and vice versa (see Figure 6). A causal loop diagram is useful for identifying various *feedback loops* in the system – *positive or reinforcing* loops and *negative or balancing* loops.

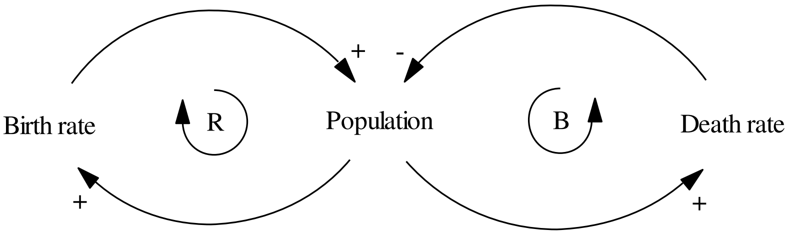


Figure 6. An example of variables (birth rate, population and death rate) connected by causal link with a polarity. R and B represent reinforcing and balancing feedback loops. Adapted from Sterman (2000)

In Paper 2, causal loop diagrams were developed to illustrate how often important systems variables are treated as isolated depending upon the system boundaries and how cause-effect relationships can be distant in space and time. The focus was on revealing the unintended environmental consequences of improvement actions within production systems to improve material and energy efficiencies per unit of product. The outcomes of intended actions that caused direct or indirect negative or undesirable effects from the perspective of an outsider and were not addressed by the actor of the actions were treated as the unintended environmental consequences.

3.3.3 Semi-structured Interviews and Product Study

Semi-structured interviews were carried out in order to gather experiences of experts during new product development from discarded materials. The interviewees were from different countries and were mainly waste management professionals and product designers working with product development from waste resources. The interviews lasted between 40 to 90 minutes and were carried out in person (22 interviews) or by video-conferencing over the internet (three interviews). All interviews were recorded for future referencing and analysis (for more details see Paper 3).

The interviewees were introduced to some important definitions used in the interview, e.g. waste, municipal solid waste and professional designer. Two examples were then used as mediating objects to illustrate new product development from discarded materials. The product examples collected during the interviews were further analysed using criteria in order to categorise them in the resource recovery routes proposed by the circular economy.

3.4 Validity of the Results

The research results were first validated during the group brainstorming sessions. Furthermore, the anonymous reviewers of the papers submitted to journals provided their outlook on the research content. Indeed, the publication review process involved an intense dialogue between the authors of Papers 1-5 and the anonymous reviewers. This dialogue often involved a clash of ideologies due to different understandings of the problem discussed. Indeed, different reviewers had differing opinions on the manuscripts, with some supporting the views expressed and others heavily criticising them. Nonetheless, during the review process we were able to convince the reviewers, after establishing a fruitful dialogue and common understanding of the problem under study. Therefore, the group brainstorming activity and the peer-review process (reviews of journal papers and the thesis) could be viewed as validating the overall results.

3.5 Limitations of the Study Design

As mentioned earlier, the work involved a significant amount of qualitative inferences. Stakes (2010) describes some of the general characteristics of qualitative research as: (i) *interpretive* (acknowledging the subjective views of the researcher on the results); (ii) *experimental* (viewing reality as a human construction); and (iii) *situational* (directing objectives in a unique set of contexts). Some of these characteristics may be apparent in the way various research questions are approached in this thesis and the reader may have other interpretations. Indeed, this was experienced in the comments of some of the peer-reviewers of Papers 1-5. Nonetheless, Andersson et al. (2014) argue that narrative/qualitative approaches theorising about complex systems have some advantages over mainstream complexity science predominantly based on reductionist ideals such as static mathematical and system dynamics models, e.g. the qualitative approaches can handle the heterogeneity, contingency and multilevel nature of complex systems. The results presented in this thesis do not represent an end but rather a beginning of holistic thinking on physical resources from a global sustainability perspective. Indeed, the thesis is a daring attempt to establish a dialogue on current practices rather than simply defending the inferences presented.

4. Summary of the Results of Papers 1-5

"Thoroughly conscious ignorance is the prelude to every real advance in science"
James Clerk Maxwell (1831-1879)

This chapter gives a brief summary of the results obtained in Papers 1-5. Paper 1 contributed mainly to the first objective of the thesis by identifying the major challenges facing the global waste management system. Papers 2-4 highlighted the limitations in the current approaches to physical resource management and identified necessary system transitions towards more sustainable global resource management. Paper 5 identified the sustainability challenges facing global physical resource management.

4.1 Paper 1

Jagdeep Singh, Rafael Laurenti, Rajib Sinha, Björn Frostell (2014). Progress and challenges to the global waste management system. *Waste Management & Research* 32 (9), 800–812. doi:10.1177/0734242X14537868

In Paper 1, a literature review on progress and challenges to the global WM system was performed and quantitative data on global waste generation and management were analysed. The findings were then further evaluated in a global context. Based on this evaluation, it was concluded that the current isolated approaches in different systems for WM, waste reduction and resource management are indeed insufficient in a long-term sustainability perspective. This is mainly because the end-of-pipe focus of these approaches fails to address the various challenges facing the WM system. Thus waste management operations are carried out within technical, economic and environmental constraints to minimise the impacts from these wastes, rather than in a coherent approach to waste prevention throughout the production and consumption system. Paper 1 identified some of the major challenges facing the global WM system managing the outflows of (waste) physical resources as: (i) inextricable link between economic growth and waste amounts; (ii) increasing complexity of product composition and variety in the production and consumption systems; (iii) lack of environmental awareness; and (iv) barriers to practical implementation and performance of various approaches to waste management. These challenges highlight some of the underlying root causes of the (waste) resource outflows from socio-economic systems (end-of-life products and the elementary flows of solid, liquid and gaseous wastes), which in turn result in resource depletion and environmental impacts. Some of these challenges were further investigated in Paper 3 (Section 4.3).

Globally, only municipal waste generation is on the top of the societal agenda, while the wastes due to production activities (resource extraction and manufacturing) are relatively less well recognised. Recognising production wastes on a global scale is very important not only due to the ecological impacts arising from the very high volumes of these wastes produced, but also from a resource point of view. This is particularly important for production activities that are highly globalised. Indeed, in recent decades, there has been increasing globalisation as a result of companies shifting their production to low- and middle-income countries with cheap labour resources and less stringent regulations. The consuming nations thereby also out-source a major part of their waste generation, and only account for the wastes due to use and final disposal of a product. The conclusion in Paper I was that the increasing industrial waste generation rates in low- and middle-income countries can be ascribed to increasing imports/consumption in high-income importing countries. This is highly unsustainable due to the fact that low- and middle-income countries tend to lack WM infrastructure. This shows that the sole focus on municipal waste streams does not recognise the real intensity of waste issues. Furthermore, the databases show fragmented information on waste generation and management, and thus also fail to reflect the overall situation of global WM. This creates a need for establishment of life cycle-based databases reflecting the actual global waste situation.

In a thermodynamics perspective, socio-economic systems 'metabolise' physical resources into useful products together with solid, liquid and gaseous outflows of wastes. Furthermore, the useful products eventually become waste at the end of their life cycle. In view of the sustainability challenges created by rapid *outflows* of *waste resources* from socio-economic systems, Paper 1 highlights the need for an integrated approach to WM to account for and control all kinds of solid, liquid and gaseous emissions and wastes. Such an approach can provide a holistic picture of physical resource metabolism in society and help to devise pro-active management strategies in the upstream systems of production and consumption.

To address the challenges to the global WM system, a broader systems approach to resource management is proposed in Paper 1. This approach demands a common understanding of the resource problem at global level, which involves identifying various actors, sub-systems and causal mechanisms in the broader system of product design, production, consumption and WM to the necessary control of gaseous, liquid and solid wastes from all these activities in the environment (as illustrated in Figure 7). Creation of joint visions among various actors must be based on clearly defined objectives or coordination principles for the transition path toward the system goals. This implies developing a holistic view of the unified system of resource metabolism in society with the following main system objectives:

1. *Reducing residues/wastes/emissions throughout the system of production and consumption and WM.*
2. *Maintaining resource quality throughout the life cycle of the resource.*
3. *Establishing a world-wide shared vision among businesses and society.*

To achieve these objectives, implementation of a new innovative consumption model is needed, where reuse and repair, re-manufacturing and resource recovery are supported and minimum resources enter and leave the socio-economic system (the inflows and outflows mentioned in Section 1). To foster efficient cycles of reuse and resource recovery, maintaining resource quality throughout the product chain is imperative. Waste prevention and minimisation approaches in different socio-technical systems (production, consumption and waste management) should be further developed to deal with spatially and temporally dispersed waste problems due to globalisation. This establishes a bridge between the WM agenda and the issue of long-term physical resource management planning in a global context, as highlighted in Paper 5.

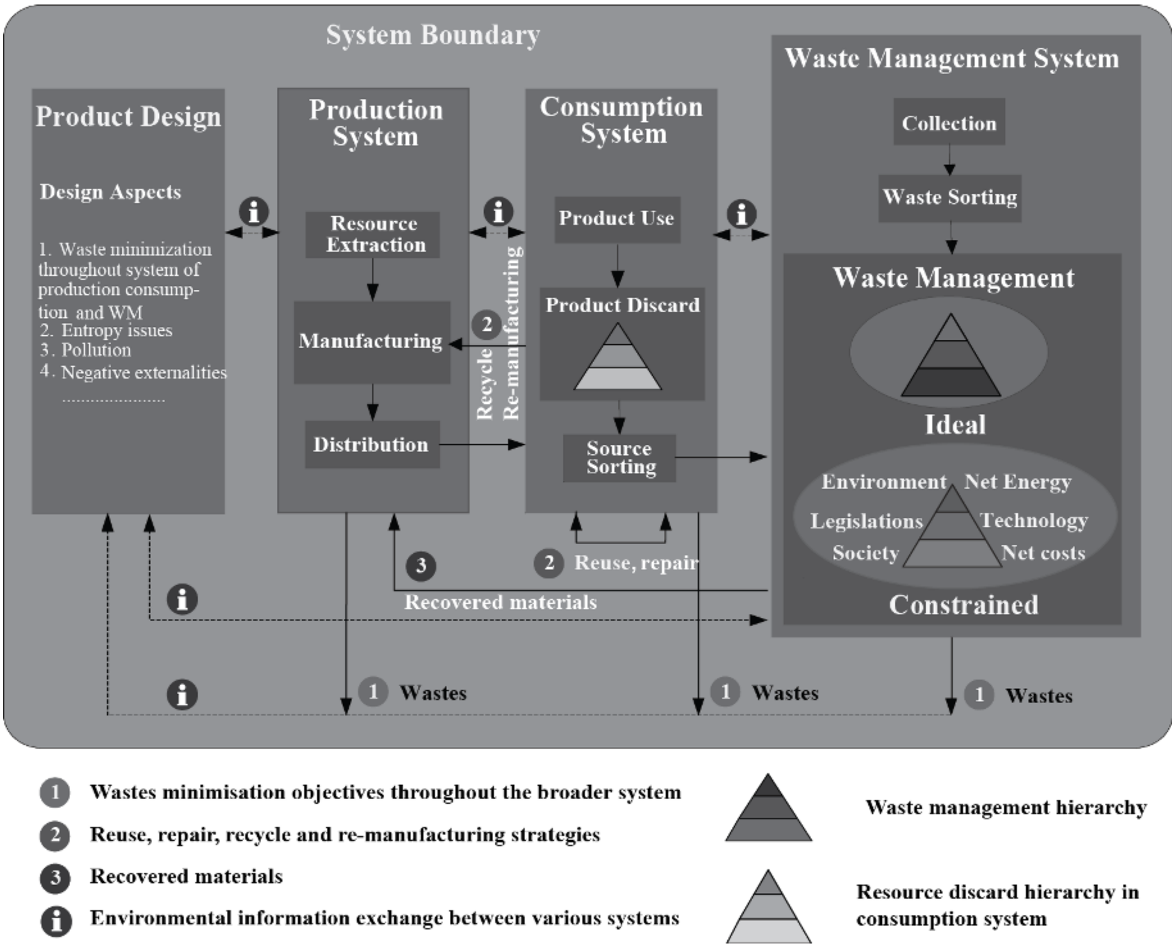


Figure 7. System interactions, processes and information flow in a broader design, production, consumption and WM system. The resource discard hierarchy in the consumption system refers to the hierarchical decisions of repair, reuse, re-manufacturing and disposal of products/resources, while the WM hierarchy refers to waste treatment options in the WM system. The product design system incorporates environmental aspects throughout the life cycle chain of a product along with other design aspects

4.3 Paper 2

Rafael Laurenti, **Jagdeep Singh**, Rajib Sinha, Josepha Potting, Björn Frostell (2015). Unintended environmental consequences of improvement actions: A qualitative analysis of systems structure and behaviour. *Systems Research and Behavioral Science* (in press). doi: 10.1002/sres.2330

In order to identify and conceptualise the problem of wastes in a broader context, Paper 2 qualitatively analysed the current system of production and consumption and possible strategies for waste prevention (resource management) throughout the system. The system structure and behaviour of production and consumption systems responsible for unintended environmental consequences of purposive actions to improve material and energy efficiencies were explored. A highly inter- and transdisciplinary literature review was performed in order to bring together knowledge and theories from different fields. This integrated knowledge was then utilised to explore the unintended negative social and environmental externalities to production and consumption activities that are the outcomes of an economic/industrial activity on agents having no stake/say in the transaction involved. Causal loop diagrams were used to explore and visualise the system structure generating these unintended consequences of purposive actions in the domain of physical consumer goods: (1) How incremental improvements in material and energy efficiencies result in an increased consumption; (2) how this increased consumption causes wastes and pollutions to increase; and (3) how this can result in social and environmental negative externalities, economic inequalities and other broad unintended consequences in society (see Figure 8). However, the main focus in Paper 2 was to discuss the unintended negative (environmental and social) impacts of incremental innovations and therefore Figure 8 does not depict the positive environmental and social impacts due to these innovations (except economic growth and lower consumer costs).

The main conclusion in Paper 2 was that increasing material and energy efficiencies has been employed as a major strategy to decouple economic growth and environmental impacts and that, in addition to positive economic and environmental benefits, this has also led to unintended negative environmental consequences.

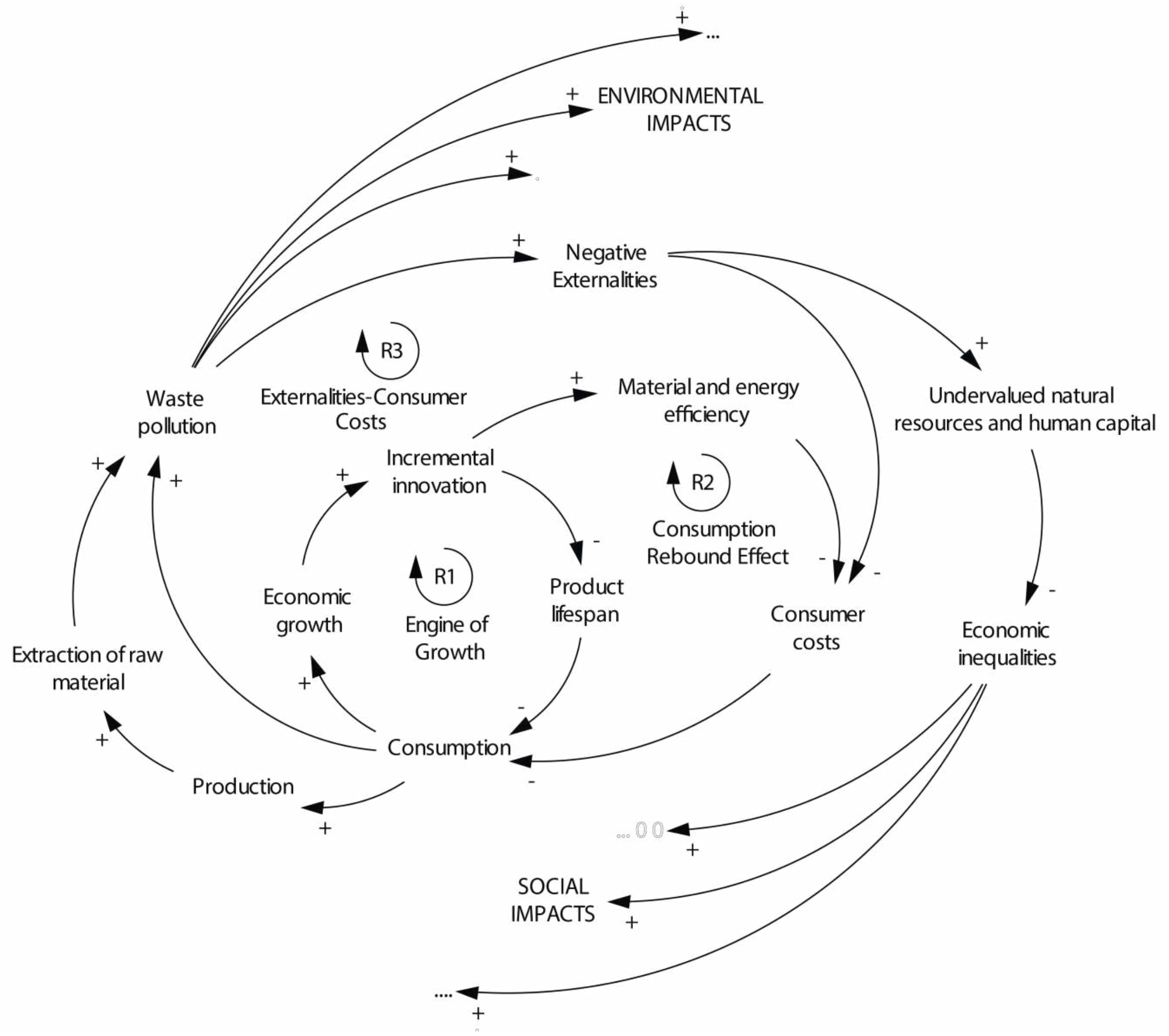


Figure 8. Social and environmental unintended consequences caused by increased generation of wastes and pollution and economic inequalities as a result of the reinforcing loops of Engine of Growth (R1), Consumption Rebound Effect (R2) and Externalities-Consumer Costs (R3)

The reinforcing factors driving negative environmental and social impacts in the system analysed were found to be consumption and incremental innovations. Two potential modes of behaviour to address these impacts were explored: product-service system and environmental policy. Product-service system aims to decouple economic growth from environmental impacts by intervening in material consumption and incremental innovations. Figure 9 represents the balancing feedback loop 'New Growth' based on product-service system. This loop can also reinforce another feedback loop, 'Circularity', by increasing reuse and recovery of physical resources in production and consumption systems, thus reducing waste and pollution.

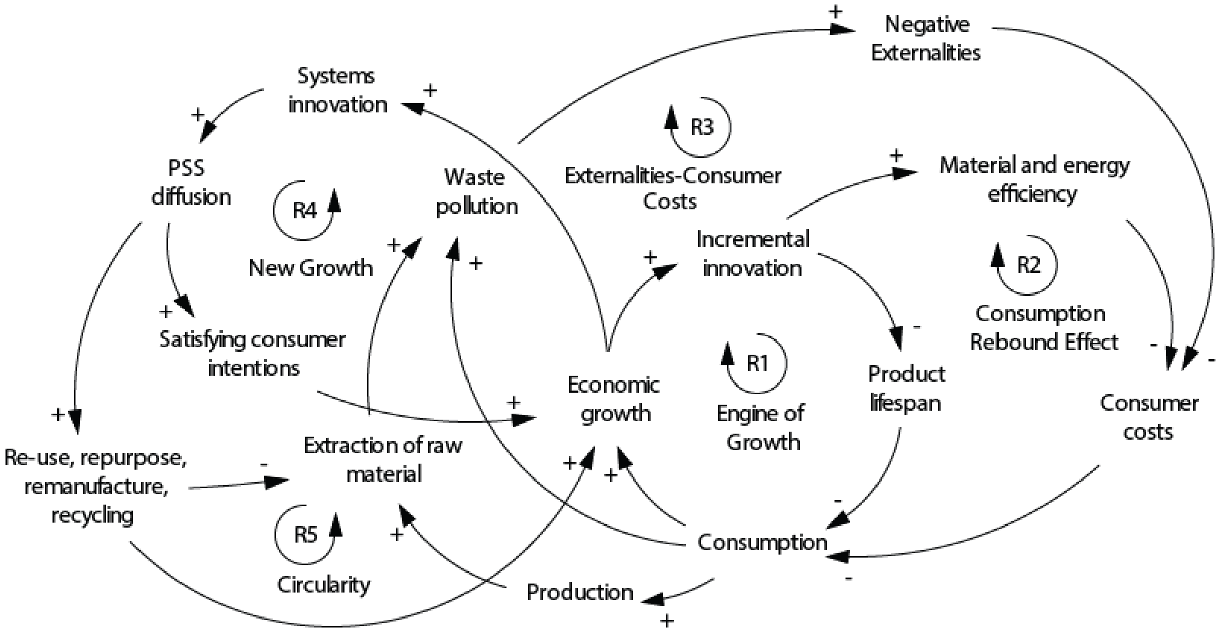


Figure 9. Reinforcing New Growth loop (R4) and Circularity loop (R5) to reduce waste and pollution throughout production and consumption systems

According to the results in Paper 2, achieving decoupling of economic growth from resource consumption requires a holistic understanding of the complex social logic of economies. Moreover, transition from an incremental innovation-based economic growth paradigm to a product-service system-based growth paradigm requires system innovations in consumption patterns, business models, physical infrastructure and product/system design. The current economic system does not account for negative externalities, i.e. negative environmental and social impacts of production and consumption activities. The conclusion in Paper 2 was that externality taxes as a policy instrument for internalising the full cost of production and consumption activities can be expected to create a balancing loop to reduce pollution and wastes (see Figure 10).

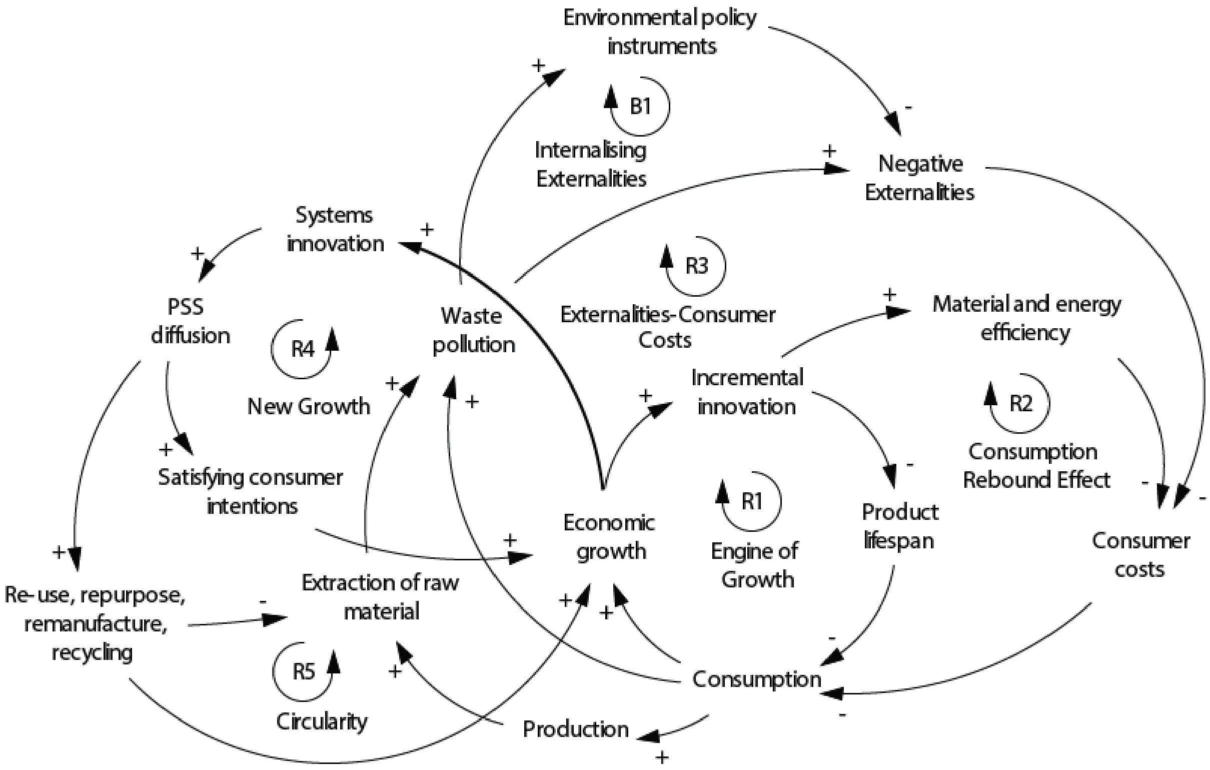
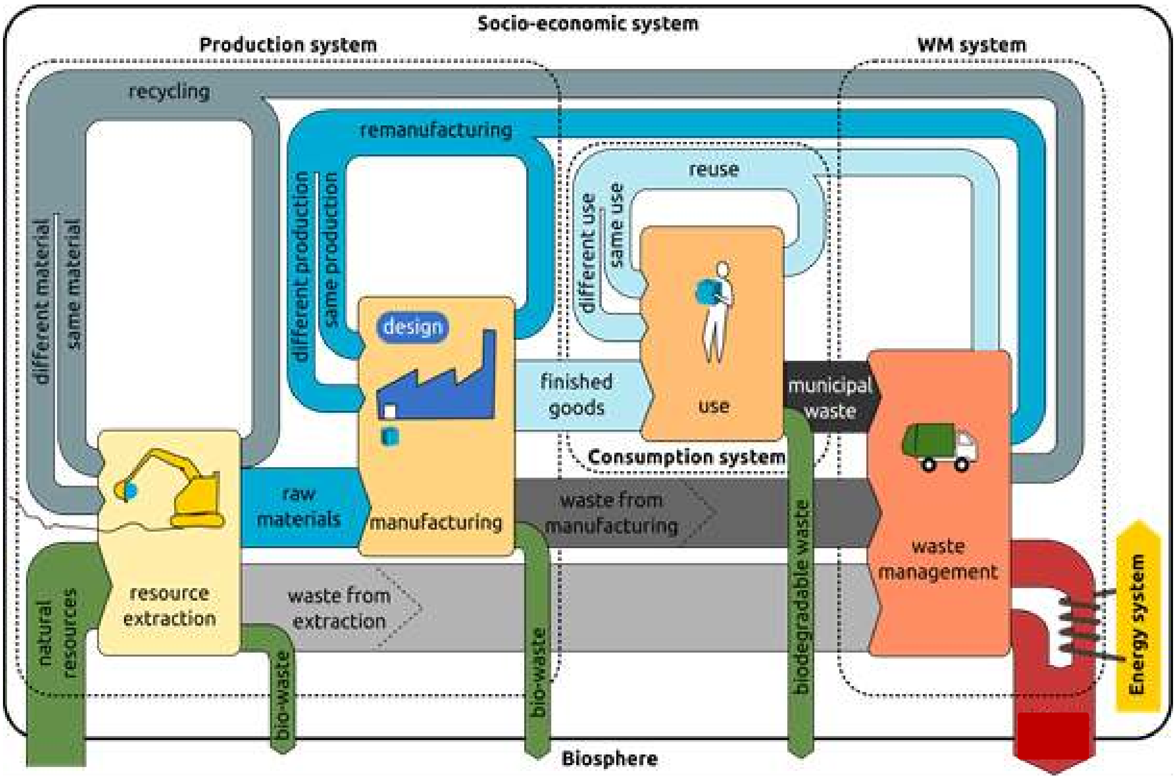


Figure 10. Balancing feedback loop Internalising Externalities (B1) reducing the wastes and pollutions throughout production and consumption systems

4.2 Paper 3

Jagdeep Singh, Isabel Ordoñez (2015). Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy (in press). *Journal of Cleaner Production*. http://dx.doi.org/10.1016/j.jclepro.2015.12.020

In Paper 3, some of the major challenges to global WM discussed in Paper 1 were investigated in the context of resource recovery from discarded products not initially designed for end-of-life recovery (from a product design or system design perspective). The study examined how resource quality could be maintained throughout the system of production and consumption systems by identifying the challenges product designers face while closing the material loops. Therefore, it attempted to address the objectives of the broader systems approach to resource management proposed in Paper 1. For this purpose, semi-structured interviews were carried out with waste management professionals and product designers working with product development from waste materials. A detailed literature survey was conducted to gather examples of products developed from waste material streams. In total, 58 distinct examples of products/materials developed from post-consumer discards were collected, further studied and classified based on criteria describing: Product type (same or different product), value of the recovered material or product, production process involved (handmade or serial), waste type (post-consumer or industrial waste) and availability of separate collection and recycling system (available or not) (see Appendix 2 for more information). These practical examples led to a categorisation of resource recovery routes in practice where designers played an important role in closing the material loop (see Table 4 and Figure 11).



Wastes for final disposal

Figure 11. Proposed model to illustrate possible material flows through society, including resource recovery routes

Table 4. Examples grouped by recovery route and described following the chosen criteria. '=' and '≠' indicate that the case where the new product developed from the discard was the same as the (discarded) original product and different, respectively. '>', '=' and '<' represent the cases where the value of the new product was more, the same and less, respectively, than the discarded product utilised to create it

Recovery route in circular economy	***Total***	***Product***		***Value***			***Production***		***Waste type***				***Recycling system***		
		=	≠	<	=	>	Hand Made	Serial	Industrial	Post-consumer	Both mixed	Waste prevention	Yes	No	Varies
Reuse	*3*	*3*	*-*	*-*	*3*	*-*	*	*1*	-	*2*	-	*1*	-	*1*	*2*
Maintenance	*3*	*3*	*3*	*-*	*3*	*3*	*3*	*3*	-	*3*	-	-	-	*3*	-
Remanufacture	*22*	*1*	*21*	*2*	*2*	*18*	*12*	*10*	*6*	*15*	-	*1*	*5*	*14*	*3*
Recycle	*22*	*3*	*22*	*4*	*5*	*13*	-	*22*	*1*	*18*	*2*	*1*	*17*	*5*	-
Biodegradable	*3*	-	-	-	-	-	-	*3*	-	*3*	-	-	*1*	*2*	-
Energy recovery	*2*	-	*2*	*2*	-	-	-	*2*	-	*2*	-	-	*1*	*1*	-
Total cases summarised	***55***	***10***	***48***	***8***	***13***	***34***	***15***	***41***	***7***	***43***	***2***	***3***	***24***	***26***	***5***

3 *Examples did not fit any recovery routes*

Total Examples ***58***

▨ *Repeated examples that belonged to multiple categories*

* *Second-hand markets and charity organisations are not production processes to be considered as handmade or serial*

The main conclusions in Paper 3 were as follows:

1. Approximately half of the 58 product examples identified involved remanufacturing, but the actual amount of material remanufactured was much less than the total volume of recycled materials. This indicates huge potential for remanufacturing if these discards are separated from the waste streams.

2. Most of the post-consumer discards were utilised to develop products different from the original product type utilised as raw material, because the actors involved in developing most of these products were not original manufacturers. This indicates that if product 'take-back' systems, organised by the original manufacturers, are in place, these resources can be recirculated through remanufacturing into the same products.

3. Most of the examples involved serial production processes. This implies that most of the examples could be mass-produced if desired, strengthening

resource recirculation in society. However, this requires implementation of efficient product 'take-back' systems.

4. The economic value of most of the examples reviewed exceeded that of the original end-of-life material/product. However, the material quality was not necessarily maintained, as noted in some examples. This raises questions about the overall efficiency of such recirculation considering economic efficiencies alone. This is an important insight for the circular economy to regulate such issues among the actors in the value chain.

Furthermore, based on the interview study, Paper 3 identified four major challenges to designers seeking to close the material loops: (1) Uncertainties in the use and end-of-life phases of the product; (2) lack of market for recovered resources (products and recyclables); (3) increasing complexity of product composition; and (4) agency and ownership issues concerning waste resources. Identification of these provided important insights into challenges facing the upcoming circular economy. The conclusion in Paper 3 was that in order for the circular economy to be a successful strategy, it must: Address issues concerning the societal perception regarding ownership of products, wastes and environmental responsibility at end-of-life and devise strategies for resource recovery from more complex waste streams.

4.4 Paper 4

Rafael Laurenti, Rajib Sinha, **Jagdeep Singh**, Björn Frostell (2016). Towards addressing unintended environmental consequences: A planning framework. *Sustainable Development* 24(1). 1-17. doi:10.1002/sd.1601

As mentioned in Section 3.1, one aim of this thesis was to encourage recognition of complex phenomena within local/regional interventions in order to foster the notion of *'think globally, act locally'*, by recognising aspects of systems that are often neglected. Therefore, the analysis dealt with two extremes: i) Studying increasing system complexities while incorporating several system aspects in order to present the issues related to wastes and resources in a holistic way and ii) drawing inferences on accessible system leverage points to address the unintended consequences. Therefore, a framework was necessary to analyse: (1) how resource/waste problems are perceived and approached in the WM system and in production and consumption systems; and (2) the system boundaries to devise solutions to waste/resource problems, i.e. the sustainability agenda as demand-shaping forces within these systems. A more descriptive framework was also needed in order to make a robust analysis and suggest solutions to problems within various system scales and levels of the physical resource management system. For this purpose, the different analytical perspectives explained in Section 2 were employed to develop a planning framework to operationalise sustainable global physical resource management. This framework focuses on exploring the interconnections between physical resource flows and the socio-technical-economic drivers which affect these flows. It aspires to identification of causal mechanisms and feedback loops responsible for unintended consequences and includes three features of the systems integration procedure: (i) Setting different system boundaries (broader to narrower); (ii) accounting for causal relationships and feedbacks; and (iii) allocating responsibilities between stakeholders. Inclusion of these features within the framework is intended to address unintended environmental consequences in physical resource management. There are six steps within the planning framework:

1. *Framing the challenges – what is the challenge and why is it a challenge?*
2. *Defining the aim and developing a conceptual model.*
3. *Expanding the system boundaries – flows, stocks, drivers and their interlinkages.*
4. *Shrinking the system boundaries to accessible leverage points.*
5. *Setting goals and indicators.*
6. *Identifying management strategies to achieve goals. (Paper 4)*

These steps consist of qualitative and quantitative iterations, as illustrated in Figure 12 and described in detail in Paper 4. The proposed planning framework is illustrated using the example of a global mobile phone product system (only the results from the qualitative iteration in Figure 12 are presented).

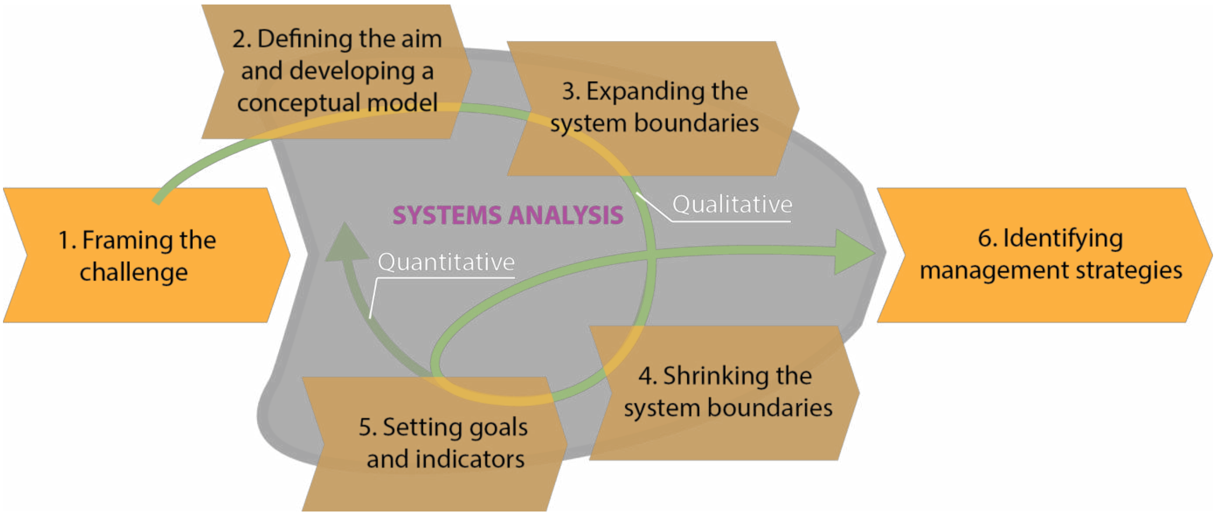


Figure 12. A planning framework for devising management strategies to address unintended environmental consequences of the current resource management paradigm. After qualitative iterations (screening), quantitative iterations (accounting, modelling and simulation) can be conducted (Paper 4)

This planning framework is viewed as the interface between sustainable development demands and the interventions (improvement actions) to respond to the sustainability challenges within the socio-economic system. The framework presents an industrial ecology view on physical resource metabolism in society. Figure 13 illustrates the proposed planning framework as an interface between sustainable development demands and an enterprise, where the WM system is analysed as part of the broader product design, production and consumption, and waste system. The framework helped to depict a fuller picture of the sustainable challenges (demand-shaping forces) linked to current resource management paradigm and also to reveal the gaps in system knowledge and management practices.

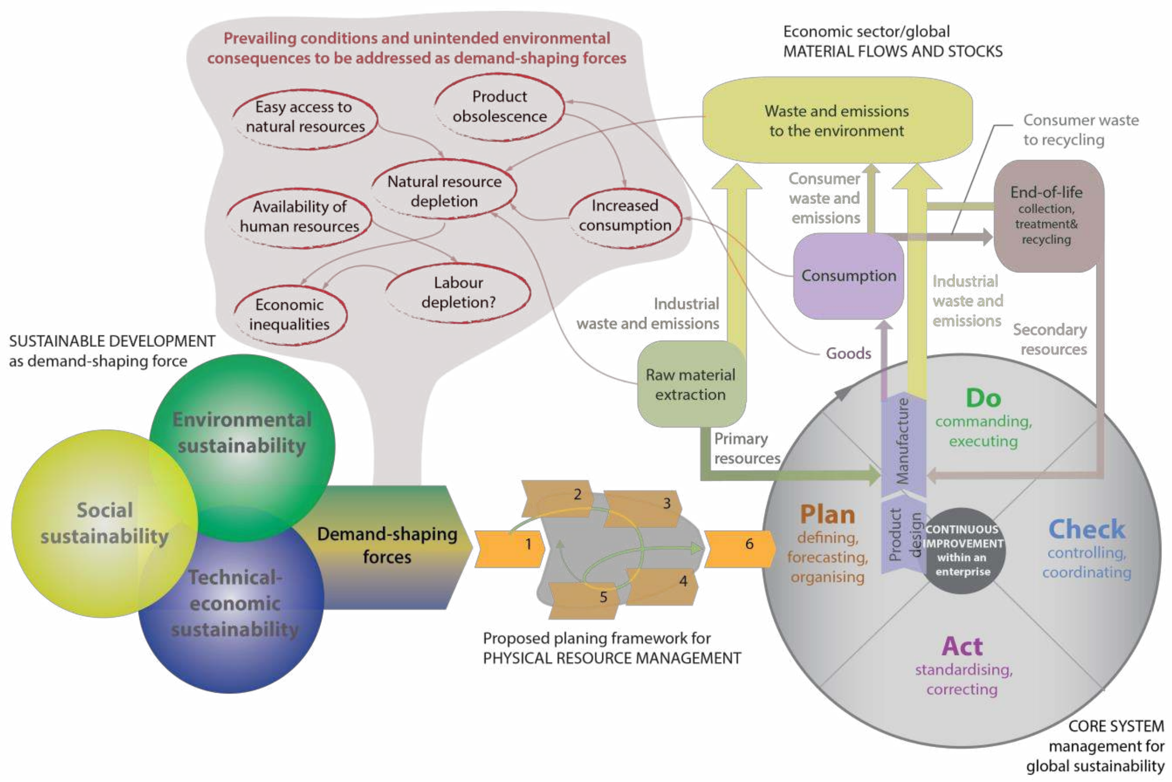


Figure 13. Illustration of the proposed planning framework as an interface between sustainable development demands and an enterprise (Paper 4)

4.5 Paper 5

Jagdeep Singh, Björn Frostell (2016). Towards a Concerted Approach to Sustainable Global Physical Resource Management. *Manuscript.*

Sustainability challenges facing current global physical resource management due to the increasing production rates of some important physical resources were analysed in Paper 5. These physical resources included some of the major resources for energy (oil, natural gas and coal), agricultural yield (phosphorus, water and zinc) and industrial production (the rare earth and precious metals). A literature review was conducted in order to: (a) collect data on peak extraction rates, annual production and global reserves for these key natural resources as a proxy for global resource urgencies; and (b) understand the drivers for the increasing global resource metabolic trends and the broad sustainability constraints. Peak and longevity estimates were also analysed in a global context.

Analysis of yearly longevity estimates for the physical resources studied showed that, despite the increasing production rates, the longevity of most of these physical resources (except coal, zinc, gold, platinum-group metals and antimony) has been increasing in the past two decades (see Figure 14). Trends for growing global reserves and production rates indicate the success of intensified technological efforts discovering new reserves and/or efficiently exploiting existing reserves (see more information on global production rates and resource reserves in Appendix 3). The increasing longevity of many of the resources studied indicates that there are no immediate constraints to resource supply with current resource extraction rates, as long as these efforts are able to satisfy *the logic of supply-demand* in society with business as usual. However, considering that these resources are finite, there will eventually be technological and economic constraints to exploiting the resource reserves – the so-called 'peak', after which production rates will start to decline. With the current trends for increasing inflows of the resources studied (cf. Appendix 3), the physical resource management system could face technological and economic constraints very soon. Indeed, the peak data in

Table 5 show that the extraction rates of several of these resources will peak in the coming 30-40 years. Furthermore, global reserves of gold, silver, copper, zinc and antimony can only sustain their current production rates for 15 to 30 years (cf. Figure 14 and Appendix 3). The longevity of global reserves of oil and phosphorus has increased over the past two decades. However, although the global reserves of natural gas have more than doubled, its longevity has not increased due to the increasing production rate. This indicates that the global community could simultaneously face supply shortage/risks for several of these resources due to economic, technological and social constraints.

The overall conclusion in Paper 5 was that despite the increasing longevity estimates over the study period, the current increasing inflows of the physical resources studied are unsustainable in a global sustainability perspective. Moreover, it was shown that the resource supply risks for many of the key resources studied have not reduced, despite the increasing global reserves over the past two decades. In a global context, Paper 5 emphasised the need for recognising and managing the ecological constraints to the increasing inflows of physical resources and the outflows of wastes and emissions. To sustainably manage the inflows, the inter-resource dynamics among various inter-dependent resources should be recognised and managed. For sustainable management of the outflows, there is a need to design and manage anthropogenic stocks and sinks of physical resources in society, so that they can be in use for a long time and can be reintroduced to society.

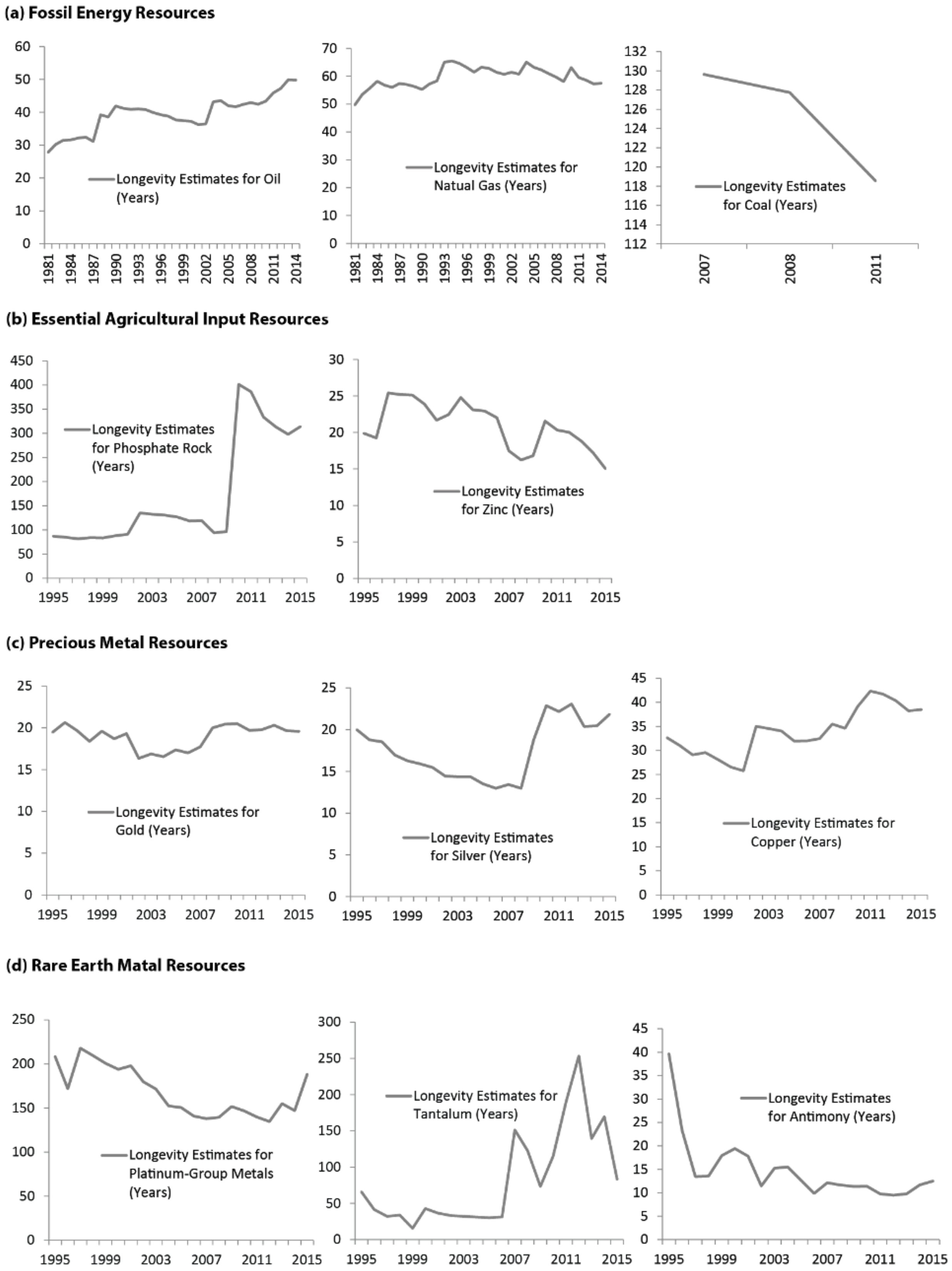


Figure 14 Yearly longevity estimates for the physical resources studied, based on their global reserves and annual production rates. The sources of data are U.S. Geological Survey and the World Energy Council

Table 5 Year of 'peak' extraction rates for different material resources

	Peak Year	Comments
1. Fossil Energy Resources		
Coal	2020	According to Energy Watch Group estimates (cf. Zittel et al. 2013, p.11)
	2040	According the U.S. Energy Information Administration (2013, p.4), world coal production will peak around 2040, followed by a much slower growth rate.
		At the 2013 rate of coal extraction, world coal reserves of 1052 billion tons will be depleted in 135 years (cf. World Coal Association 2015).
	2042-2062	(Maggio & Cacciola 2012)
Gas	2020	According to estimates in Bentley (2002).
		According to a report published by the U.S. Energy Information Administration (2013, p.63), the reserves-to-production ratio is 64 years.
	2020	According to Energy Watch Group estimates (Zittel et al. 2013)
	2070	According to World Coal Association (2015)
	2024-2046	(Maggio & Cacciola 2012)
Oil	2030	(Sorrell, Miller, Bentley & Speirs, 2010)
	2040	(International Energy Agency 2014, p.2) The 2014 estimates of reserves were 7% higher than the 2012 estimates, mainly due to new discoveries of reserves in Venezuela.
	2010-2015	Supply and demand are likely to diverge between 2010-2015 (Owen, Inderwildi & King, 2010, p. 4749)
	2009-2021	(Maggio & Cacciola 2012)
2. Essential Agricultural Inputs		
Phosphorus	2030	High-grade resource will be depleted within 50-100 years (Smil 2000). However, recent estimates show that global reserves can last for 309 years if consumed at the 2015 rate (U.S. Geological Survey 2016, p.125).
Zinc	n.d.	15 years of stock at the 2014 production rate (U.S. Geological Survey 2016, p.193).
Water	n.d.	According to United Nations Environment Programme (2007a), 1.8 billion people globally will suffer water scarcity due to physical, economic or environmental constraints.
3. Precious Metals		
Gold	2022-2025	Global gold reserves can supply the demand equivalent of 2014 for only 18.6 years (cf. U.S. Geological Survey 2016, p.73)
Silver	n.d.	With use of 5-7 g/capita & year, silver reserves can last for about 50 years (Johnson et al. 2005; Gordon et al. 2006). However, recent estimates by the U.S. Geological Survey show that at the 2015 production rate, global stocks of silver will be exhausted within 21 years (2016, p.153).
Copper	2100	Global copper reserves will finish in 39 years with the rate of extraction in 2014 (U.S. Geological Survey 2016, p.55).

(continued on the next page)

4. Rare Earth Industrial Materials		
Antimony	n.d.	Only 13 years of reserves at the rate of extraction in 2014 (U.S. Geological Survey 2016, p.25) and a high supply risk (Graedel, Harper, Nassar, Nuss & Reck, 2015, p. 4259).
Indium	n.d.	Quantitative estimates of reserves not available (U.S. Geological Survey 2016), but a recent study (Graedel et al., 2015, p. 4259) confirms that indium supply is very high supply risk.
Platinum-group metals	n.d.	171 years of reserves of platinum-group metals (platinum and palladium) at the 2015 production rate, but the estimates were 188 years due a lower production rate due to a 5 month long strike in major mining companies in Africa (U.S. Geological Survey 2016, p.127). However, according to Gordon and Colleagues (2006, p.1213), platinum stocks will only last for 15 years.
Tantalum	n.d.	Global reserves will last for 83 years (U.S. Geological Survey 2016, p.167).

5. Discussion

"Science is always wrong. It never solves a problem without creating ten more."
George Bernard Shaw (1898-1943), in a toast at a dinner celebrating Einstein.

The thesis explored a number of social, technical, economic and environmental aspects associated with current production and consumption activities. However, it predominantly applied an ecological sustainability viewpoint to physical resource management challenges. Therefore, the results merely 'scratch' the surface of the tremendously complex real-world realities. Notwithstanding its limitations, the thesis demonstrates some implications of current approaches to resource management which must be addressed in order to secure a sustainable future. This chapter discusses some of the important results of the thesis, their limitations and opportunities for future research.

5.1 Transition from WM to a Physical Resource Management Paradigm

Globally, the current WM model throughout the production and consumption system predominantly focuses on removing the waste *generated* and treating it with the available best technologies within economic and environmental constraints. However, too little attention is paid to the causal mechanisms in the production and consumption systems outside the boundary of WM system to (i) *avoid* waste generation and/or (ii) achieve *sustainable* WM.

In addition, the sole focus on managing municipal solid waste from consumption systems disregards the true severity of overall waste generation (solid, liquid and gaseous) during the resource extraction and production processes. Indeed, the achievement of high rates of resource recovery from municipal solid wastes by some Western countries[10] represents only a partial reality of the WM system, since it does not reflect the overall waste generation due to the highly resource-intensive consumption in those countries, which is often outsourced globally. As shown in Paper 1, because of the globalised operations of production, consumption and WM, the objectives of sustainable resource management cannot be realised without a life cycle perspective on resources and wastes. Thus, there is need to establish a worldwide shared vision on resource (waste) issues among society and businesses.

Furthermore, resource management encompasses numerous aspects (technical, economic, environmental and social), a multitude of actors and complex driving mechanisms. Some of these intricate aspects and mechanisms are qualitatively illustrated in the causal loop diagrams in Paper 2. That paper also investigates two alternative modes of system behaviours – product-service system and environmental policy instruments (see Figure 10), which address the issues of negative environmental externalities in the form of residues, wastes (solid and liquid) and emissions (gaseous). The current level of system complexity managing scarce natural physical resources is probably inadequate with regard to the complexity of the challenges to the global WM system described in Paper 1. There is a need to develop a holistic view on the end-products and by-products of production and consumption processes, including all the solid, liquid and gaseous emissions. Indeed, reducing the generation of wastes and emissions throughout the system of production, consumption and WM requires fostering ideas of new design, reuse, repair, remanufacturing and recycling in the upstream systems of production and consumption, as illustrated through the potential modes of system behaviours in Paper 2. This involves careful management of the material flows in a circular model of resource consumption maintaining resource quality. McDonough and Braungart (2008) classified such material flows as: biological nutrients, designed to re-enter the biosphere and build natural capital, and

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[10] Such as Austria, Netherlands, Denmark and Sweden.

technical nutrients, designed to circulate at high quality without entering the biosphere.

The proposed broader systems approach to resource management is based on a transition from a linear to a circular model of resource consumption. This approach aims to achieve non-depletion of resources and zero waste and highlights the need for a holistic understanding of the entire system of production and consumption, including the multitudes of perspectives, cross-scale dynamics and actor interactions at all levels. The approach suggests that the stocks of resources entering the human activity system should be designed and managed in such a way that they can be re-introduced again into the human activity system.

Despite the preliminary character of the proposed approach, it accentuates the limitations of the current WM paradigm as regards addressing the intricate challenges facing sustainable global resource management. For example, it revealed that despite relatively well-developed infrastructure for WM, the overall severity of waste issues remains with developed countries due to their high levels of resource consumption, which cause wastes owing to production activities (resource extraction and manufacturing) in other regions.

5.2 Important Role of Product/System Designers in Achieving Sustainable Global Physical Resource Management

The product design phase decides most of the environmental features of a particular product system. Product design plays an important role in selecting materials, substances or chemicals suitable for, or easily manageable by, different WM processes. Examples include use of aluminium or biologically degradable material to improve the recovery of packaging waste or use of renewable resources for products with a short life-span which, after cascade use, can easily be treated biologically and be re-introduced to the biosphere. This requires implementation of economy-wide product design approaches that integrate broad environmental objectives in the product design process. Indeed, as long as the product design for any existing product is not optimised for reuse of all the materials, even the best recycling method will fail to achieve the desired sustainable outcomes.

Another important aspect is the system design to recover discarded products at their 'end-of-use'[11] and/or 'end-of-life' phase. As Paper 1 shows, the increasing complexity of product composition and variety in the production and consumption systems poses challenges for existing collection systems that are designed to collect a limited number of waste fractions, rather than facilitating reuse, repair and remanufacturing operations. Paper 3 highlights the opportunities and challenges for existing reuse and remanufacturing waste streams, which are not designed to close the material loops from product and system design perspectives.

Thus, product and system designers can play a very important role in the development of efficient resource management. Designers need a vision of a better life in tomorrow's society and a clear understanding of their role, their possible contribution to and responsibilities in the transition towards sustainable resource management (Deutz et al. 2013). Without the contribution of designers, the full potential of sustainable production and consumption, and thus sustainability, cannot be realised. Similarly, only in a sustainability perspective can the full potential of design be realised (Spangenberg et al. 2010). The challenge for designers is to concurrently consider product functionality, cost, value, consumer preferences and environmental impacts in the design process. In relation to a systems understanding of sustainability challenges, the field of product design may need to re-examine the normative and evaluative premises underpinning current approaches to design products.

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[11] Here, this term refers to the case when a user discards a product because it is not needed anymore or for other reasons, but the product is in perfect shape to be reused by other users. Khetriwal & First (2012) suggest various triggers and influencers of obsolescence and disposal of durable products.

5.3 Role of Society in Achieving Sustainable Global Physical Resource Management

Papers 1 and 5 highlight the sustainability challenges facing the global physical resource management due to the increasing outflows of (waste) resources to natural sinks and the increasing inflows of physical resources to the human activity system. These challenges together constitute the management aspects of resource urgencies and the anthropogenic stocks of physical materials in the human activity system from local to global level. Furthermore, Papers 1-5 all repeatedly emphasise the need for societal integration at local to global level in the quest for sustainable management of physical resources and recognise the important roles and responsibilities of: a multitude of actors such as consumers, enterprises, producers, recyclers and policy makers; and institutions such as businesses, manufacturing companies, mining industries, political bodies, WM authorities etc.

Papers 2 and 3 give prominence to the role of a circular economy in addressing resource management challenges. Paper 2 qualitatively illustrates the role of product-service systems to achieve resource circularity and decouple resource consumption and waste generation from economic growth (Figure 10). Paper 3 stresses that the implementation of much demanded increased reuse, repair, remanufacturing and recycling operations within a circular economy is not possible without active participation by consumers. Within such an economy, consumers' roles and responsibilities go beyond mere appropriate disposal of waste to also include a shift in consumer behaviour towards waste prevention through environmentally conscious purchasing and consumption behaviour.

Enterprises can play a vital role in realising systems fostering sustainable physical resource management. Paper 4 proposed a planning framework as an interface between an enterprise and sustainable development demands, in order to minimise the unintended environmental consequences. However, enterprises alone cannot address the broad objectives of sustainable physical resource management, especially in the absence of incentives. Paper 2 highlights the role of environmental policy instruments internalising negative environmental and social externalities to foster feedback loops enabling resource circularity. However, since production and consumption chains act globally, establishing and facilitating these global value chains requires global-level socio-political support to achieve resource circularity. Therefore, there is an important role for policy makers in implementing sustainable development demands along with economic growth aspirations. The framework presented in Paper 4 could facilitate a worldwide shared vision on physical resource management that includes social, economic and environmental impacts linked to production and consumption activities. This could further assist in clarifying the roles and responsibilities to be borne by different actors through the causal relationships among these actors, the physical resource exchanges and the impacts (positive and negative) from these material transactions.

Thus, all sections of society have a role to play in the transition towards sustainable global physical resource management. However, a clear understanding and implementation of these roles in society will require environmental awareness and willingness to act in an environment-driven agenda from an individual to a national/international political level. One could argue that global society at present has no clear understanding of its roles in managing global commons, which could be largely responsible for the gaps in how we are currently managing society. In this regard, Paper 1 argues that due to the sole focus on post-consumer wastes and a lack of life cycle-based statistics representing all residues, wastes and emissions, the real severity of overall waste generation and its environmental impacts are largely unknown.

Most of these roles and responsibilities are still prescribed to be carried out within a municipal/local/regional administrative boundary, whereas these should be performed in a global context. Expanding the system boundaries of the current WM paradigm to include product design, production, consumption and waste systems, as proposed in Paper 1, is a step towards understanding and linking the global context of local consumption dynamics. Such a systems approach to resource management truly links local actions to global concerns such as resource scarcity and environmental pollution.

5.4 Some Pervasive Challenges to Achieving Sustainable Global Physical Resource Management

The need to recognise and manage ecological constraints to increasing inflows of physical resources and outflows of wastes and emissions in a global sustainability perspective is demonstrated in Paper 5. Such an approach to physical resource management could require striving to achieve a sustainable level of physical resource consumption. Some studies (United Nations Environment Programme 2014; Bringezu 2014; Bringezu 2011) have proposed sustainable levels of global per capita material metabolic rates as:

- 10 tons per capita & year global metabolic rate as a policy target, as suggested by Stefan Bringezu (2011, cf. 2014, p.58). Bringezu (2014, p.41) explores *"which meaningful targets that could be set, internationally and by individual countries, with regard to their global resource consumption, in order to ensure a sustainable use of resources"*.

- 6-8 tons per capita & year global metabolic rate as one of the targets for sustainable resource management at global level (United Nations Environment Programme 2014, p.9; United Nations Environment Programme 2011a). The International Resource Panel has proposed incorporation of a separate goal on sustainable resource management within the sustainable development goal (cf. United Nations Environment Programme 2014, p.8). The International Resource Panel explores different scenarios with the intention of illustrating the implications of normative assumptions for economic growth and development models for resource consumption (United Nations Environment Programme 2011a).

A comparison of proposed sustainable global physical resource metabolic rates against current metabolic rates indicates that the metabolic rates of India (13 tons of physical materials/capita & year) and China (15 tons of physical materials/capita & year) alone exceed the global average sustainable level (cf. United Nations Environment Programme 2011a). Thus, meeting the global sustainable level of metabolic rates is indeed a challenge not only for developed countries, but also developing countries. This suggests that addressing this vital challenge undoubtedly requires a global common vision on resource issues. Such a common vision must incorporate the various inflows, including resource urgencies such as peaks, outflows of wastes and emissions, and present and future demands on physical resources.

The current management of physical resources represents a global-level 'tragedy of the commons' situation. Therefore, sustainable global physical resource management must regard normative issues related to justice. These issues include the distribution of burdens, the rights and fundamental interests of all global communities and the ultimate responsibility for actions to repair environmental damage. The physical resources required to fulfil fundamental interests, or rights, should be given priority over the resources required for fulfilling desires[12]. Indeed, developing countries will require growth in the supply of scarce energy resources to meet their basic needs and improve life expectancy (Lamb & Rao 2015). Therefore, saving a scarce resource to be used for satisfying the basic needs of developing nations could be considered a global legitimate duty. Resource consumption for the fulfilment of desires of actors with an already high welfare level should be appropriately fined or restricted. However, making such distinctions between needs and desires is a pressing issue in the field of environmental philosophy. The global community needs to consider and address such ethical uncertainties. As suggested by the political philosopher Henry Shue, "*one person's desire for an additional jar of caviar is not equal in urgency to another person's need for an additional bowl of black beans*" (Shue 2014, p.124).

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[12] Normative concepts such as 'rights' and 'fundamental interests' here play the role of identifying what would constitute fair access to a resource. Rights, in this sense, aims towards protecting fundamental interests (such as right to life, health, subsistence, etc.) (cf. Caney 2005, p.767; cf. Raz 1986). If an agent has the right to subsistence and a current amount of a specific resource is required to protect that right, it is permissible for the agent to consume a specific level of that resource. However, the agent is not entitled to usage that exceeds the protection of those fundamental interests, as it could deprive others of their fair share.

Thus, achieving a sustainable level of resource consumption may require: (i) an improved joint understanding of the problem; (ii) a shared sense of urgency among different actors as a prerequisite to facilitating envisioning of 'better' solutions; and (iii) a common objective. However, due to the global-scale planning and implementation involving long time frames involved, these also mean dealing with various types of uncertainties or gaps. Weiss & Thakur (2010) describe five such gaps that exist between the nature of many current global problems and their solutions – knowledge gap, normative gap, policy gap, institutional gap and compliance gap. As far as the knowledge gap is concerned, existing statistics are very limited in terms of their use in understanding global physical resource dynamics. Indeed, for sustainable global physical resource management, life cycle-based databases are needed. These databases must include resource use, waste generation and associated environmental, social and economic impacts, in order to interlink this information in a broader system.

Furthermore, in today's globalised economic system, resource consumption and associated environmental damage are often spatially and temporally distant. Therefore, an additional issue concerns to whose 'account' environmental degradation of production activities should be ascribed – that of the producing nation, or that of the consuming nation that instigated the production? Such causal links are not always clearly apparent[13] (cf. Jamieson (2010) for a discussion on causal and moral responsibility in relation to climate change). However, such issues should be addressed to manage various environmental and social risks. Responsibility in a political sense is often limited to the responsibility of nation states. This is highly unsatisfactory, as political institutions, being limited to the next two or three election cycles for a very limited part of the global population, are ill-equipped to manage both the required temporal and spatial scales of such

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[13] According to the philosopher Dale Jamieson (2010), moral responsibility often requires causal efficiency as a necessary condition. However, in issues with such grand scales as global resource management, the causal influence is not always manageable or identifiable, due to the involvement of many actors and extended time frames (see Jamieson (2010) and van de Poel et al. (2012) for a discussion on moral responsibility and the problem of many hands).

scales (cf. Gardiner (2011), who considers such institutional shortcomings to be a cause of the moral tragedy of climate change).

Globally, multilateral diplomacy and collective action are required to solve several shared problems. For instance, global governance already exists, in one form or other, for several issues such as nuclear energy, politics, military and economics. However, resource scarcity issues are not yet on the agenda in the international political sphere. The unavailability of global-level institutional and governance systems shows the ineptness of our resource-dependent global society to counter the man-made risks linked to resource scarcity/depletion. Establishment of these systems is vital to ascribing responsibility for setting and governing sustainable global physical resource management and assigning environmental damage or gains. Current trends in resource consumption demand establishment of a global-level institution to address sustainability challenges associated with physical resources and to highlight the resource issues at global level.

Resource scarcity/depletion is a global sustainability challenge and global institutions must perceive it as an urgent issue to be addressed. Addressing the gaps mentioned previously is a tremendous geopolitical challenge. Civil institutions such as research institutes, academia and think-tanks could contribute to fill these gaps to a great extent. Yet, the final step in operationalising solutions at a global scale would require the consensus of global political institutions on these gaps and their commitment to meet various sustainability challenges. Therefore, global consensus and commitment to respond to sustainability challenges is of the utmost important in progress towards sustainable global physical resource management. Indeed, incorporation of a separate goal on sustainable resource management under the UN sustainable development goals, as proposed by The International Resource Panel, is an important step in this direction (cf. United Nations Environment Programme 2014, p.8).

Overall, this thesis shows that the current approaches to physical resource management fail to fully recognise the issues discussed above and therefore neglect an important component of sustainable development, namely society. Sustainable global physical resource management must address not only the technological and ecological issues related to resources, but also the social issues in a global perspective. This suggests a need for increased inter- and/or trans-disciplinary discourse in order to understand resource management challenges and active participation by the global society to make real progress towards sustainable global physical resource management. This may require a radical shift in existing business structures, consumer behaviour and values, and governance regimes.

Sustainable global physical resource management would address these global sustainability challenges by building up natural stocks of physical materials and improving the resilience of natural systems to assimilate the outflows of residues/wastes/emissions (Figure 15). Within such a resource management philosophy, anthropogenic stocks of physical resources within the human activity system could be efficiently managed with minimum physical resource *inflows* from the natural stocks and minimum *outflows* of residues/wastes/emissions to the natural sink. Global sustainability concerns such as global equity and justice would be inherent attributes of the activities managing the physical resources from local to global level.

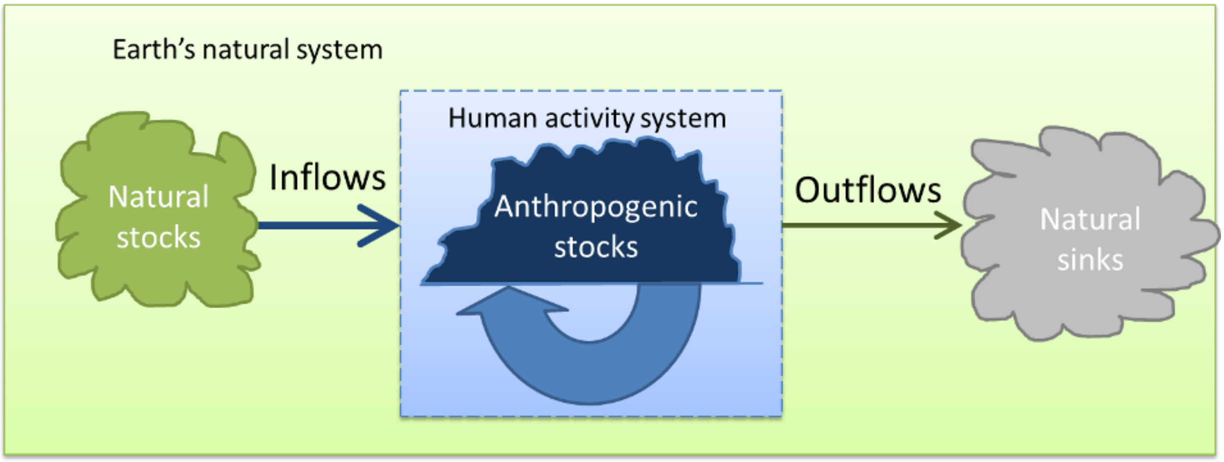


Figure 15. Illustration of sustainable global physical resource management

5.5 Limitations to the Study and Opportunities for Further Research

Addressing broad sustainability challenges linked to increasing inflows and outflows of physical resources requires more research than could be carried out within the scope of the present thesis. However, the thesis highlights the need to broaden WM system boundaries to include these challenges in problem formulation and devise solutions at local/regional level to reduce resource consumption. Indeed, this is a vital challenge in today's globalised production and consumption chains with their multitude of actors and institutions. These actors and institutions can play an important role in the physical resource management system. In future work, I intend to explore such actors and institutions and their roles and responsibilities to foster such a vision. In the present thesis, I aimed to convey a way of thinking, rather than pure knowledge, on sustainable global physical resource management addressing ecological sustainability challenges associated with inflows, stocks and outflows of physical resources.

It should be noted that the broader systems approach to resource management proposed in Paper 1 and the planning framework proposed in Paper 4 are primarily derived from qualitative inferences concerning global WM issues. Therefore, this approach provides limited insights into the practical barriers to planning and implementing such an approach encompassing different actors with their respective, often conflicting, interests.

The causal loop diagrams developed in Paper 2 could be further developed to include many other causal links and feedback loops. For example, those presented here could be extended to include the positive consequences of improvement actions (intended or unintended). There could also be a possibility to quantify various causal variables in the causal loop diagrams. Paper 2 proposed internalising environmental impacts with environmental policies (taxes and incentives) as a main driver: (1) to enhance more service-based consumption to reduce material consumption; and (2) to close the gap between low- and high-income households in order to maintain the status quo due to potential prices increases, while still assuming that other things such as income remain the same. This is quite opposite to the current notion of economic growth focusing only on increasing income rather than harming consumers in order to protect the environment. Further studies could be designed to study: The kinds of policies required to maintain a sustainable level of income and achieve environmental goals at a global level; how consumers should be educated to contribute to global sustainability objectives by motivating them to: (i) avoid buying products they could avoid; (ii) purchase and use products in an environmentally conscious way; and (iii) discard products at their 'end-of-life' in an environmentally sound way.

Furthermore, the proposed planning framework in Paper 4 could be validated using real-world cases where planning and implementation of initiatives fostering environmental and social sustainability take place with the active participation of actors throughout the production and consumption chain.

The product study in Paper 3 included 58 distinct examples of resource recovery from post-consumer wastes. The findings could be further strengthened by including more such product examples.

As highlighted in Paper 1, to foster efficient cycles of reuse, for example remanufacturing and reassembly, it is important to investigate the potential of a system to concentrate or dilute the resources. An approach described by Rechberger and Brunner (2001) could be employed to quantify the potential of a system to concentrate or dilute resources. Such studies can be helpful in addressing root causes for material losses throughout the system, and consequently, in planning and implementing strategies for better physical resource management.

Further research studies could be devised to address some of the gaps highlighted in Section 5.4. One of the issues relevant to the planning of sustainable global physical resource management would be to develop a framework for life cycle-based databases on resource use and waste generation. Such databases could be helpful in linking physical resource consumption to waste generation, resulting in better resource management strategies.

Discussion

This thesis predominantly investigated the ecological sustainability challenges in current approaches to physical resource management. To advance the proposed sustainable global physical resource management approach, further studies could be conducted to analyse the economic and social aspects associated with physical resources, e.g. to define a fair share of a resource and explore frameworks ascribing responsibility for environmental damage due to production and consumption activities. Indeed, there are several issues to be considered: what scientists could offer by providing information and structuring the information on what needs to be done; the kinds of resources needed at various levels; and how new technological advances and discoveries could contribute to the quest for sustainable global physical resource management.

6. Conclusions

The overall aim of this thesis was *to investigate the (ecological) sustainability challenges facing current approaches to physical resource management* in systems of production and consumption and waste management and to identify the *necessary system transitions towards more sustainable global physical resource management.* Overall, it was concluded that the current isolated approaches in different systems for waste management, waste reduction and resource management are indeed insufficient in a global sustainability perspective. There is currently no holistic approach to physical resource management that includes the global sustainability concerns associated with: increasing inflows of physical resources to the human activity system and increasing outflows of (waste) resources to the natural stocks assimilating these outflows. Furthermore, current approaches fail to recognise issues relating to global equity and justice.

The three objectives listed in Section 1.2 were addressed as follows:

1. *Investigate the challenges facing current global waste management*

It was concluded that despite considerable technological progress in waste minimisation and treatment, the current waste management system still faces several vital challenges, including: (i) inextricable links between economic growth and waste amounts; (ii) increasing complexity of product composition and variety in the production and consumption systems; (iii) lack of environmental awareness in a life cycle perspective; and (iv) barriers to practical implementation and performance of various approaches to waste management.

The thesis highlights that increased international trade has 'decoupled' production and consumption centres. The conclusion reached from this was that high-income importing countries are stimulating (industrial) waste generation in low- and middle-income countries. Therefore, despite improved infrastructure for post-consumer waste management in high-income countries, the overall severity of existing waste issues rests with high-income countries due to their high levels of resource consumption. Furthermore, current waste statistics fail to show actual waste generation in a systems perspective.

Overall, global waste management is on an unsustainable trajectory due to the increasing waste generation rates and relatively less well-developed infrastructure for waste management in low- and middle-income countries and high rates of resource consumption in high-income countries.

2. *Identify and highlight the main limitations to current approaches to physical resource management*

Issues explored were: (i) the challenges to current product/system design practices for sustainable physical resource management; (ii) the limitations to incremental innovations in material and energy efficiencies, in a global sustainability context; and (iii) the limitations to current resource management approaches in addressing global sustainability challenges.

Analysis of examples of product systems revealed huge potential for reuse and remanufacturing and showed that current production, consumption and waste management systems are '*make-use-dispose*'-centric rather than '*make-use-remake*'-centric circular systems. Therefore, these systems do not support much needed reuse, repair and remanufacturing. In order to establish a circular economy for a broad range of products/services, systems and products require a new design philosophy.

It was concluded that current product/system design practices to close material loops must address challenges arising from uncertainties regarding product life phases, especially how the products will be handled during the use phase and at their end-of-life phase; the quality of products developed from discards; resource recovery from more complex waste streams; the societal perception of the products developed from discards; and ownership of the discarded products.

Purposive actions to improve energy and material efficiencies in the domain of physical consumer goods can result in consumption rebound effects that have unintended negative environmental and social consequences of increased overall resource consumption and generation of wastes and pollution. These unintended consequences arise because current approaches do not recognise and embrace the complexity underlying these consequences with a holistic perspective prior to implementation of action. The conclusion in this thesis was thus that current approaches lack the level of system integration required to address the physical resource management challenges in globalised production and consumption systems.

3. *Highlight necessary system transitions towards a more sustainable global physical resource management*

It was shown that a concerted approach to physical resource management, including product design, production, consumption and waste management, is needed to decouple negative environmental and social impacts from economic growth. Some necessary system transitions towards sustainable global physical resource management were identified.

A broader systems approach to resource management is proposed to address the root causes of the challenges facing the current global waste management system. This approach implies developing a holistic view of the unified system of product design, production, consumption and waste management. Within such an approach to resource management, product/system designer would be required to address sustainability issues in their design process, along with considering the traditional design features. Some of the most pressing challenges are to: address societal perceptions regarding ownership of products and wastes, and environmental responsibility at their end-of-life; and devise strategies for resource recovery from more complex waste streams.

In order to reduce the negative environmental and social externalities due to current production and consumption systems, it was concluded that a new growth paradigm is needed in which product-service systems and environmental policy instruments are used to address the externalities. New approaches to resource management in industries that meet broader sustainable development demands are also needed. In this context, this thesis proposes a planning framework that includes a much broader range of issues in continuous improvement activities in a new philosophy of physical resource management for global sustainability. This framework could facilitate much needed system integration by expanding the system boundaries to address global sustainability challenges. These new system boundaries should explicitly account for causal relationships and feedback loops and identify responsibilities among the key stakeholders.

These system transitions must be carried out in light of the global sustainability challenges associated with inflows of physical resources to the human activity system; outflows of residues/emissions/wastes from the human activity system; and current and future needs for physical resource stocks in the human activity system. New types of life cycle-based databases are needed to plan these transitions. This may require a radical shift in existing business structures, consumer behaviour and values, and governance regimes at a global level.

In order to achieve sustainable global physical resource management, the current global waste management practices definitely needs to transition towards a new paradigm in which the concept of waste management is broadened, as summarised by United Nations (1991, p.6) almost 25 years ago:

> *"a process of change in which the concept of waste management is gradually broadened to eventually include the necessary control of gaseous, liquid and solid material flows in the human environment, emphasising precautionary actions."*

Thus calls for a change in the waste management philosophy have been made long ago. However, as the unsustainable trajectory of the current global waste management shows, such voices have not been fully heard in society. Thus global society has a very important role to play in anticipating and realising the goals of sustainable global resource management.

7. Appendices

Appendix 1. List of the Main Research Topics and the Literature Reviewed

Research topic	Main areas covered	Sources
Current global situation of resource/ waste flows	• Resource consumption dynamics, waste flows to the environment, product discard • The current global waste management situation • Municipal solid waste and industrial waste management in developing and developed countries	(Blanchard 1992; Chalmin & Gaillochet 2009; Gerbens-Leenes et al. 2010) (Gordon et al. 2006; Graedel et al. 2015; Graedel & Voet 2010; Hardin 1968; Holden et al. 2014; International Energy Agency 2014; Rockström et al. 2009; Schmidt-Bleek 2000; Smil 2000; Sorrell et al. 2010; Steffen et al. 2015; U.S. Energy Information Administration 2013; U.S. Geological Survey 2016; United Nations 2014; United Nations Environment Programme 2014; United Nations Environment Programme 2007a; United Nations Environment Programme 2011a; Weizsäcker et al. 1997; World Coal Association 2015; Zittel et al. 2013; Bringezu 2011; Bringezu 2014; Bentley 2002) (World Bank 2012; World Bank 2005; United States Environmental Protection Agency 2012; United Nations Environment Programme 2010; Weiss & Thakur 2010)
Progress in waste management and waste minimisation Challenges to the global resource management system	• *Current resource management approaches:* technological and operational innovations in production and consumption systems to tackle waste and resource issues, eco-design, industrial symbiosis, energy recovery, extended producers'	(Anonymous 1991; Ayres 1994; Ayres & Kneese 1989; Bai & Sutanto 2002; Baker et al. 2004; Barbero et al. 2012; Bartelmus 2003; Bartl 2014; Bleischwitz 2003; Blumenthal 2011; Boons & Howard-Grenvile 2009; Brunner 2007; Bylinsky 1995; Carrillo-Hermosilla et al. 2010; Cartwright 1999; Chalmin & Gaillochet 2009; Crabbe n.d.; Deutz et al. 2013; Dubois 2012; EEA 2002; Ehrenfeld 2010; Ehrenfeld & Gertler 1997; El-Haggar 2007a; EU 2008; EU 2012; Fedrigo & Hontelez 2010; Fell et al. 2010; Foundation 2012; Foundation 2014; Frosch & Gallopoulos 1989; Frostell 2013; Geng et al. 2012; Geng et al. 2010; Gentil et al. 2011a; Gerbens-Leenes et al. 2010; Gottberg et al. 2010; Gottberg et al. 2006; Gram-Hanssen 2010; Gungor & Gupta 1999; Habitat 2010; Kaenzig & Wüstenhagen 2010; Korhonen 2004; Krantz 2010; Kronenberg & Winkler 2009; Lavee 2007; Lehtoranta et al. 2011; Lenzen & Peters 2010; Lifset 1993; Lindhqvist 2000; Marshall & Farahbakhsh 2013; Mbeng et al. 2009; McDonough & Braungart 2002; McKerlie et al. 2006; MORI

	responsibility. • *Challenges:* Increasing waste amounts, technological challenges to manage the new complex waste streams, environmental awareness, barriers to practical implement-ation and performance of resource management approaches.	2002; Munasinghe 2010; Nye & Hargreaves 2010; OECD 2006; OECD 1998; Ordonez & Rahe 2013; Otto & Wood 2001; Spangenberg et al. 2010; Sternlicht 1982; Stiles 1996; Tanskanen 2000; Tudor et al. 2007; Tukker et al. 2010a; Tukker et al. 2010b; United Nations 1993; United Nations Environment Programme 2011b; Walls 2006; World Bank 2005; Velis et al. 2009; Velis et al. 2012; Vergragt 2010; Vesilind et al. 2007; Wiek et al. 2012; Wiesmeth & Häckl 2011; Wilson 2007; Wilson, Parker, et al. 2012; Wilson, Rodic, et al. 2012; Wilson et al. 2013; Wilson et al. 2006; Wilts 2012; Wilts et al. 2011; World Bank 2012; Yuan et al. 2006; Zorpas & Lasaridi 2013; Cash et al. 2006; He et al. 2013; Gößling-Reisemann 2011; Huppes et al. 2011; Rechberger & Brunner 2001; Roberts 2004; Rotter 2011; Scheinberg et al. 2010; Jeffrey K Seadon 2010; Shannon 1948; Sharp et al. 2010; Lagerstedt 2003; Kumar et al. 2009; Graedel et al. 2015)
Resource recovery routes	• Resource recovery routes in circular economy and European Union's waste hierarchy: similarities and differences	(Williams 2015; Gharfalkar et al. 2015; All-Party Parliamentary Sustainable Resource Group 2014; McDonough & Braungart 2002; Ellen Macarthur Foundation 2014; Ellen Macarthur Foundation 2012; El-Haggar 2007b; Gentil et al. 2011b; Gentil et al. 2011b)
Unintended (negative) environ-mental and social con-sequences of improvement actions	• The global economic growth engine, consumption rebound effects, • Inequality, income inequality, trust, homicide, resource wars, conflicts	(Baiocchi et al. 2010; A. Greening et al. 2000; Achabou & Dekhili 2013; Acklin 2010; Ahlroth et al. 2011; Alcott 2008; Alcott 2005; Allenby et al. 2007; Allenby & Richards 1994; Allione et al. 2012; Andersson & Råde 2002; Andrews & DeVault 2009; Armstrong et al. 2015; Arvesen et al. 2011; Aryana & Boks 2012; Ascher 2001; Assessment 2005a; Atkinson & Mourato 2008; Assessment 2005b; Baas 2008; Barbiroli 2011; Barbiroli & Focacci 2009; Bardi et al. 2014; Bass 2004; Baumann et al. 2002; Baumgartner 2011; Beuren et al. 2013; Bhamra et al. 2011; Bhamra & Lofthouse 2007; Bilancini & D'Alessandro 2012; Binnemans et al. 2013; Birol & Keppler 2000; Bistagnino 2011; Bithas 2011; Bovea & Pérez-Belis 2012; Bowen 2010; Boyce 1994; Brown 2012; Buchanan 1992; Burger & Christen n.d.; Börjesson Rivera et al. 2014; Carson 1962; Clark et al. 2009; Clark 2005; Christiansen & Smith 2012; Christopher 2012; Christen & Schmidt 2012; Cohen 2010; Collado-Ruiz & Ostad-Ahmad-Ghorabi 2013; Commission 2014; Corsini et al. 2013; R Costanza et al. 1997; Robert Costanza et al. 1997; Dahmus 2014; Davis et al. 2010; Development 2000; Dinda 2004; Dobson 2007; Ehrenfeld 2005; Gerst et al. 2001; M.

		Goedkoop et al. 1999; M. J. Goedkoop et al. 1999; Goffman 1951; Hoekstra & Wiedmann 2014; Herring & Roy 2007; Hertwich 2005; Hubacek et al. 2014; Huppes et al. 2011; Huppes & Ishikawa 2011a; Jackson 2009; Jackson 2005; James 2007; Kawachi et al. 2010; Kay 2002; Kaenzig & Wüstenhagen 2010; Knight 2009; Kortelainen 2008; Krantz 2010; Kumah 2006; Liang et al. 2013; Lifset 2011; Lorenzen 2012; Lorenzi 2008; Liu et al. 2012; MacKenzie 2012; Maxwell et al. 2011; McHenry 2009; Meadows et al. 2004; Merton 1936; Mortelmans 2005; Paskov & Dewilde 2012; Partidario et al. 2010; Polimeni et al. 2008; Rockstrom et al. 2009; Rothstein & Uslaner 2005; Schneider et al. 2011; Simas, Golsteijn, et al. 2014; Simas, Wood, et al. 2014; Swilling & Annecke 2012; Thiesen et al. 2008; Thorbecke & Charumilind 2002; Turner 2008; Uslaner & Brown 2005; J. van den Bergh 2011; J. C. J. M. van den Bergh 2011; van den Bergh et al. 2011; van der Voet 2011; Warr & Ayres 2012; Weaver & Rotmans 2006; Weidema 2008; Weidema et al. 2005; Vezzoli & Manzini 2008; Vezzoli et al. 2012; Widmer et al. 2005; Wilkinson & Pickett 2006; Wilkinson & Pickett 2010; Wijkman & Rockström 2013; Yarime 2007)
Socio-political, ethical and normative aspects related to physical resource management	• Climate change, responsibility and ethics, decision-making and uncertainties, risk and responsibility, goal setting, international inequality, climate justice, burden-sharing	(Ayres et al. 2001; Allen & Gould 1986; Baard 2014; Baard & Edvardsson n.d.; Beck 1992; Bratman 1999; Caney 2005; Davidson 2014; Davies 2013; Dearing et al. 2014; Edvardsson & Hansson 2005; Gardiner 2011; Giddens 1999; Giddings et al. 2002; Hansson 1996; Hardin 1968; Hayward 2012; Holden & Linnerud 2007; Holden et al. 2014; Jamieson 2010; Ide 2015; Jamieson 2014; Janssen 2015; Lamb & Rao 2015; Le Blanc 2015; Luke 2005; Moellendorf 2014; Nihlén Fahlquist 2006; Norton 2005; Owen et al. 2010; Raz 1986; Rockström et al. 2009; Rolston III 2012; Shue 2014; Shue 1999; Shue 1993; Simon 1957; Smil 2000; Sumi 2007; van Bueren et al. 2014; van de Poel et al. 2012; van der Leeuw et al. 2012)

Appendix 2. Products/Solutions Used as Examples in the Thesis

Product	Designer	Material	Recovery route (CE)	Same/different product	Value	Clarification	Hand-made/ serial	Waste Type	Availability of recycling system
Armo sneakers[1]	Rodrigo Alonso	Handmade shoes in micro-factories as means of poverty alleviation	-	-	-	Fair trade policies, allow for diverse production system and flexible use	HM	-	No
*	Remade in Chile[2]	Several examples	-	-	-	Design contest with several examples and done in many locations	Varies	Varies	Varies
Janipad[3]		Biodegradable sanitary pad	Composting	-	Increased	Biodegradable	S	PCW	No
Eco envases[4]	Several actors		Composting	-	Increased	Biodegradable	S	PCW	Yes
Peepoo[5]	Peepoople	Biodegradable plastic toilet bag	Composting	-	Increased	Biodegradable	S	PCW	No
Biochar as fuel		-	Energy recovery	Different product	Reduced	-	S	PCW	Yes
Tyres as fuel for concrete production	Several actors	Tires	Energy recovery	Different product	Reduced	-	S	PCW	No
Fixing WEEE, component recuperation	Several actors	-	Maintenance Remanufacture	Same/different product	Maintained or increased	Repair done with technical competence	S	PCW	No
WEEE fixing and disassembly	Recycla Chile WEEE	WEEE components	Maintenance Remanufacture	Same/different product	Maintained or increased	Repair done with technical competence	S	PCW	No
orange.at/recycling	Several actors	Cellphone collection	Maintenance Remanufacture	Same/different product	Maintained or	Repair done with technical	S	PCW	No

					increased	competence			

Product	Designer	Material	Recovery route (CE)	Same / different product	Value	Clarification	Hand Made / Serial	Waste Type	Availability of recycling system
Inplum, planters[6]	Genoveva Cifuentes	Plum core agglomerate	Recycle	Different product	Increased	Biodegradable	S	IW	No
Weather-resistant planks[7]	Polyplank	Recovered thermoplastics with wood fibre	Recycle	Different product	Increased	Mixes materials	S	PCW & IW	Yes
Bricks[8]	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No
Pavement[9]	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No
Tiles[10]	Several actors	Waste incineration ash	Recycle	Different product	Increased	Incineration by products	S	PCW	No
111 Navy chair[11]	Emeco	PET coke bottles	Recycle	Different product	Increased	-	S	PCW	Yes
Flowerpots	Several actors	Recycled plastics	Recycle	Different product	Increased	-	S	PCW	Yes
Recycled polyester clothes[12]	Patagonia	PET bottles, manufacturing waste and worn-out garments	Recycle	Different product	Increased	-	S	PCW	Yes
Recycled aluminium chairs	Several actors	Aluminium cans	Recycle	Different product	Increased	-	S	PCW	Yes
Packaging for fruit exports	OKSCU	Recycled plastics	Recycle	Different product	Increased	-	S	PCW	Yes
Waste sorting containers from recycled plastic[13]	Triciclos.cl	Recycled plastic boards	Recycle	Different product	Increased	-	S	PCW	Yes

Product	Designer	Material	Recovery route (CE)	Same / different product	Value	Clarification	Hand Made / Serial	Waste Type	Availability of recycling system
Garden furniture from recycled plastics[14]	Several actors	Recycled plastic	Recycle	Different product	Increased	-	S	PCW	Yes
Recycled pallet	Hans Andersson Recycling	NA	Recycle	Different product	Increased	Made a prototype for a pallet from recycled materials in the 1980s	S	PCW	Yes
Shredded plastic for roadmaking	Several actors	Recycled plastics	Recycle	Different product	Maintained	-	S	PCW	Yes
More recycled materials in cars	Several actors	Recycled plastics	Recycle	Different product	Maintained	-	S	PCW & IW	Yes
Tectan	Tetrapack	Agglomerated Tetrapack packaging	Recycle	Different product	Reduced	Not developed further, but still done in some areas	S	PCW	Not then
Cardboard furniture[15]	ReturDesign	Cardboard	Recycle	Different product	Reduced	Designed for recycling	S	Waste prevention	Yes
Glass recycling	Several actors	-	Recycle	Same / different product	Maintained	-	S	PCW	Yes
Metal recycling	Several actors	-	Recycle	Same / different product	Maintained	-	S	PCW	Yes
Aluminium recycling	Several actors	-	Recycle	Same / different product	Maintained	-	S	PCW	Yes
Paper recycling	Several actors	-	Recycle	Same / different product	Reduced	-	S	PCW	Yes
PET recycling	Several actors	-	Recycle	Same / different product	Reduced	-	S	PCW	Yes
Profil belts[16]	Yeayea	Bike tires	Remanufacture	Different product	Increased		HM	PCW	No

Product	Designer	Material	Recovery route (CE)	Same / different product	Value	Clarification	Hand Made / Serial	Waste Type	Availability of recycling system
Furniture[17]	Showraum	Reclaimed wood, furniture	Remanufacture	Different product	Increased	Designer network that showcases remanufactured products	HM	PCW	No
Bags[18]	Retape	Magnetic tape	Remanufacture	Different product	Increased		HM	PCW	No
*	Taller Re-Crear	Several examples	Remanufacture	Different product	Increased	Workshop for handmade upcycled products	HM	PCW	Yes
Bags[19]	Demano	Discarded PVC advertising	Remanufacture	Different product	Increased	-	S	PCW	No
Wretman-stället[20]	Torstensson	Silverware production discards	Remanufacture	Different product	Increased	-	S	IW	Yes
*	Creatables[21]	Laminated industrial discard	Remanufacture	Different product	Increased	Sometimes even performs production symbiosis	S	IW	Yes
Hacking & DIY movements	Several actors	-	Remanufacture	Different product	Increased	Creative reuse, user repurposes not manufacturer	HM	Waste prevent ion	Varies
WEEE jewelry[22]	Several actors	WEEE components	Remanufacture	Different product	Increased	-	S	PCW	No
Refurbished old drawers to new bureaus[23]	SchubLaden	-	Remanufacture	Different product	Increased	Same type of product, not exactly the same product	S	PCW	No
T-shirt seat[24]	Maria Westerberg	Metal frame with woven scrap textiles	Remanufacture	Different product	Increased	-	S	IW	No
Small-scale decorative	Several actors	-	Remanufacture	Different product	Increased	-	Varies	PCW	Varies

stuff

Product	Designer	Material	Recovery route (CE)	Same / different product	Value	Clarification	Hand Made / Serial	Waste Type	Availability of recycling system
Backpacks of BSR uniforms	-	Worn-out waste picker uniforms	Remanufacture	Different product	Increased	-	HM	IW	No
Sorensen RCY men's shirts[25]	Cecilia Sörensen	Textiles, men shirts	Remanufacture	Different product	Increased	-	HM	PCW	No
Tyre baskets[26]	Several actors	Tires	Remanufacture	Different product	Increased	-	S	PCW	No
Bag made of knitted plastic bags	Several actors	-	Remanufacture	Different product	Increased	-	HM	PCW	Yes
Playgrounds and landscaping with discard[27]	Several actors	Industrial waste	Remanufacture	Different product	Increased	-	HM	IW	Varies
Ass-savers[28]	-	PP cutouts from another industrial process	Remanufacture	Different product	Increased	Production parasites	S	IW	Yes
School gym equipment as furniture	-	-	Remanufacture	Different product	Maintained	Creative reuse, user repurposes	HM	PCW	No
WEEE chair[29]	Rodrigo Alonso	WEEE encased in transparent resin	Remanufacture	Different product	Reduced	Done as an artistic installation	S	PCW	No
Bags made of sails[30]	Several actors	Old sails	Remanufacture	Different product	Reduced	-	S	PCW	No
Reline tableware[31]	Anna Bormann	White tableware	Remanufacture	Same product	Maintained	-	HM	PCW	No
Second-hand markets	Several actors	-	Reuse	Same product	Maintained	Relocation of goods to other users	-	PCW	Varies

Product	Designer	Material	Recovery route (CE)	Same / different product	Value	Clarification	Hand Made / Serial	Waste Type	Availability of recycling system
Charity organisations	Several actors	-	Reuse	Same product	Maintained	Relocation of goods to other users	-	PCW	Varies
Glass containers for ketchup or mustard used as glasses[32]	Several actors	Glass	Reuse	Same product	Maintained	Designed for reuse	S	Waste prevent ion	Yes
Product leasing	-	-	Reuse Remanufacture Recycle	-	-	Business model strategy	Repair	Waste prevent ion	-

1 http://ralonso.com/portfolio/armo-2/?lang=en

2 http://remadeinchile.cl/blog/?cat=3&paged=6

3 http://www.janipad.com/

4 http://ecoenvases.com/

5 http://www.peepoople.com/

6 http://www.remadeinchile.cl/

7 http://www.polyplank.se/

8 http://www.ecobrick.in/waste_Utilization_in_Brick_Making.aspx

9 http://nbmcw.com/articles/roads-pavements/31522-eco-friendly-pavement-blocks-of-waste-glass-fly-ash-and-dust.html

10 http://www.uiah.fi/kll/research/tiles.html

11 http://www.emeco.net/products/emeco-111n-red-111-navy-chair-red-coca-cola

12 http://www.patagonia.com/us/patagonia.go?assetid=2791

13 http://www.triciclos.cl/#inicio

14 http://www.recycledplastic.ie/index.php?cID=11

15 https://www.facebook.com/Cardboard-Interiors-by-ReturDesign-Studio-12412156074/?ref=page_internal

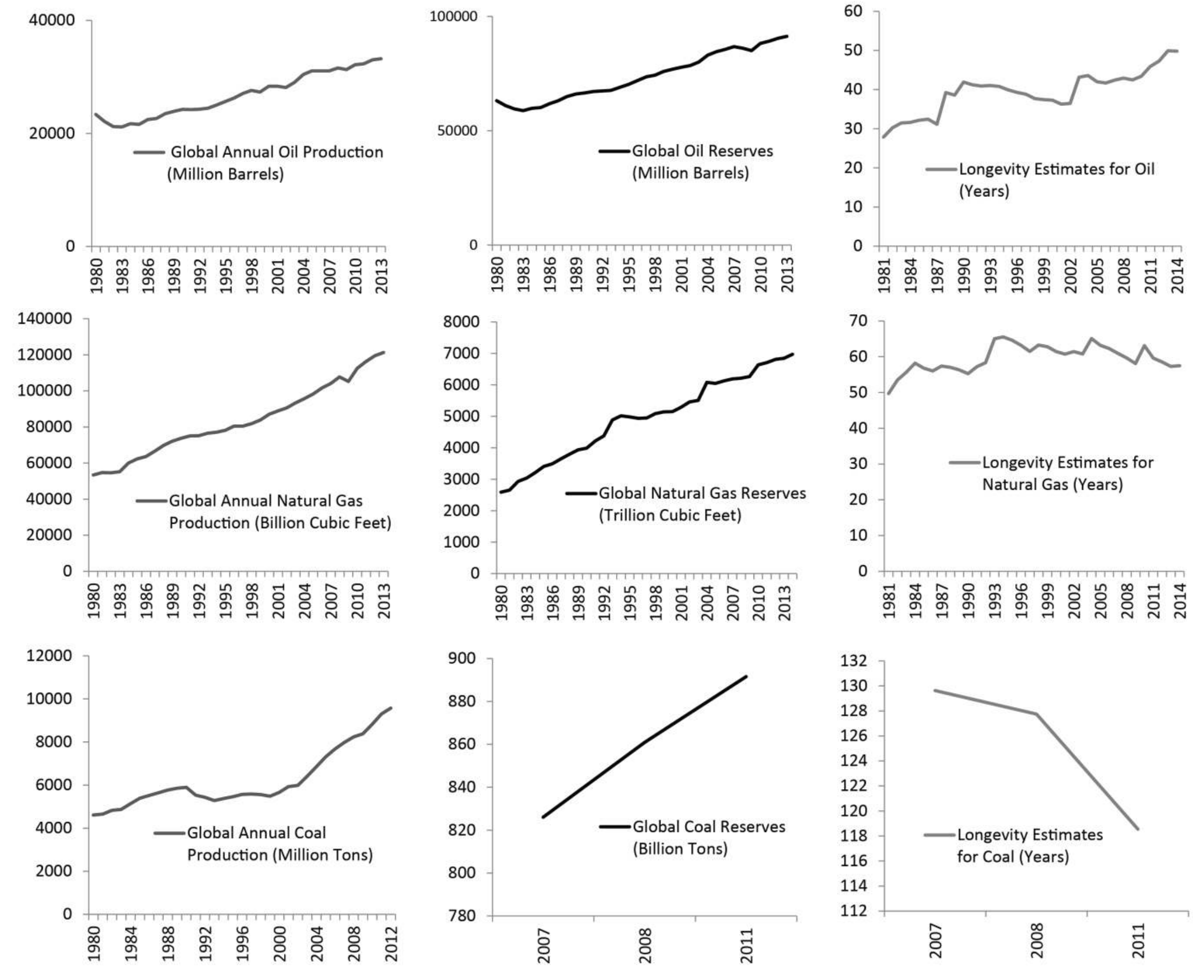
16 http://yeayea.de/

17 http://shop.showraum.de/

18 http://www.retape.de/

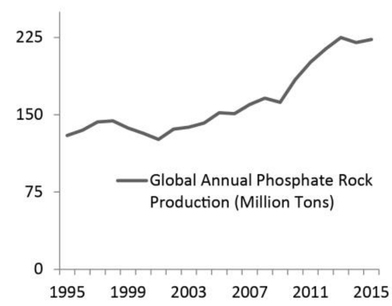
19 http://www.demano.com/
20 http://torstensson.se/product.aspx?r_id=53407
21 http://www.creatables.se/
22 https://www.etsy.com/market/electronic_jewelry
23 http://www.schubladen.de/index.php?id=moebe
24 http://greenfurniture.se/products/t-shirt-seater/?portfolioID=118
25 http://www.ceciliasorensen.com/about/
26 http://www.flattirebrand.com/#!decor/c12a3
27 http://www.maipuciudadano.cl/ecobarrios-villa-4-alamos-construira-plaza-de-juegos-con-elementos-reciclados/
28 http://ass-savers.com/
29 http://ralonso.com/portfolio/new-2/?lang=en
30 http://resails.com/
31 http://www.annabormann.de/
32 http://www.davidlebovitz.com/2011/11/mustard-glasses/

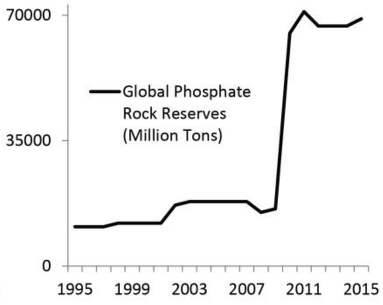
Appendix 3. Global Annual Production, Reserves and Longevity Data

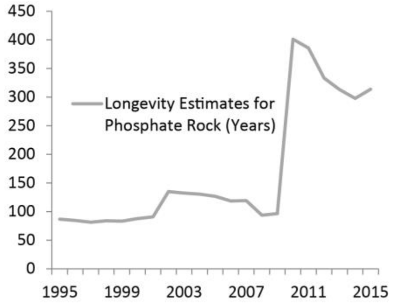


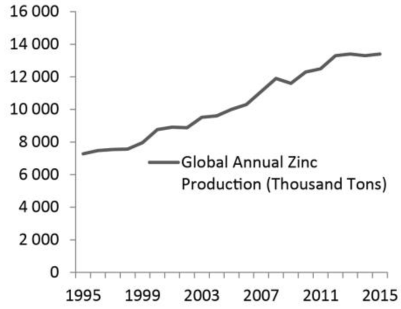
	Peak Year	Comments
Coal	2020	According to Energy Watch Group estimates (cf. Zittel et al. 2013, p.11)
	2040	According the U.S. Energy Information Administration (2013, p.4), world coal production will peak around 2040, followed by much slower growth rate.
		At the 2013 rate of coal extraction, world coal reserves of 1052 billion tons will be depleted in 134.5 years (cf. World Coal Association 2015).
	2042-2062	(Maggio & Cacciola 2012)
Gas	2020	According to estimates in Bentley (2002). According to a report published by the U.S. Energy Information Administration (2013, p.63), the reserves-to-production ratio is 63.6 years.
	2020	According to Energy Watch Group estimates (Zittel et al. 2013)
	2070	According to World Coal Association (2015)
	2024-2046	(Maggio & Cacciola 2012)
Oil	2030	(Sorrell, Miller, Bentley & Speirs, 2010)
	2040	(International Energy Agency 2014, p.2) The 2014 estimates of reserves were 7% higher than the 2012 estimates, mainly, due to new discoveries of reserves in Venezuela.
	2010-2015	Supply and demand are likely to diverge between 2010-2015 (Owen, Inderwildi & King, 2010, p. 4749)
	2009-2021	(Maggio & Cacciola 2012)

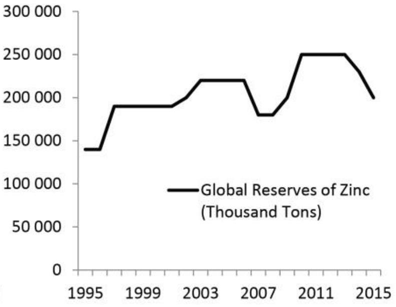
Appendices

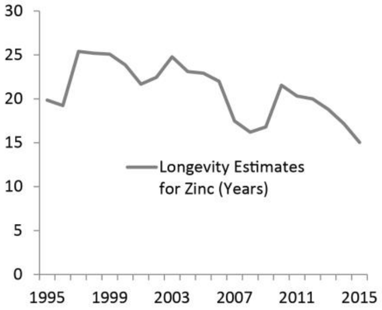




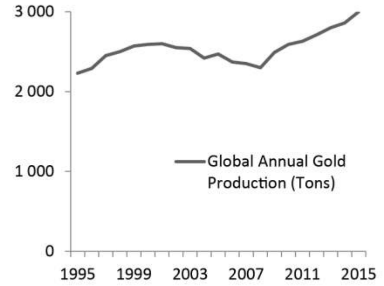


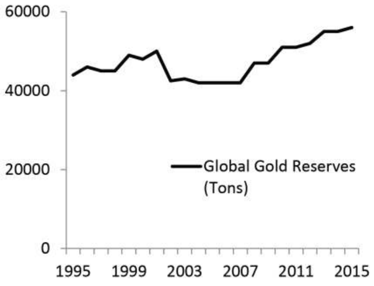


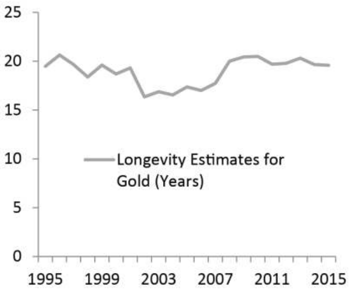


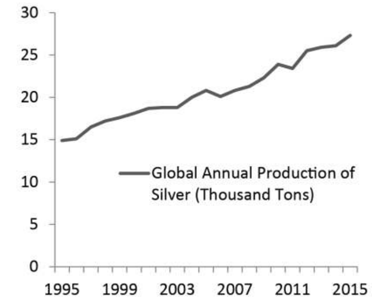


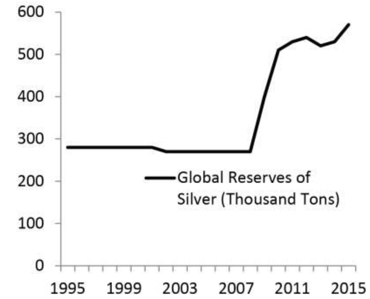
Peak Year		Comments
Phosphorus	2030	High-grade resource will be depleted within 50-100 years (Smil 2000). However, recent estimates show that global reserves can last for 309.5 years if consumed at the 2015 rate (U.S. Geological Survey 2016, p.125).
Zinc	n.d.	14.9 years of stock at the 2014 production rate (U.S. Geological Survey 2016, p.193).
Water	n.d.	According to United Nations Environment Programme (2007a), 1.8 billion people globally will suffer water scarcity due to physical, economic or environmental constraints.

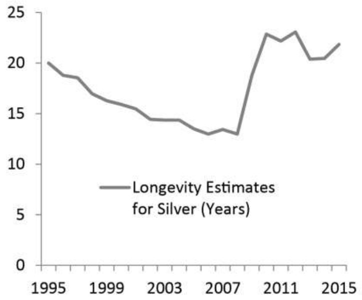


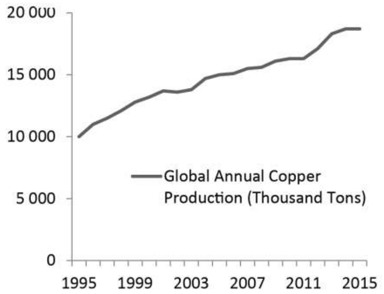


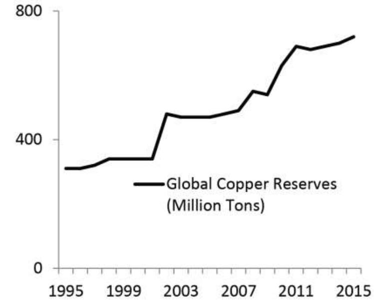


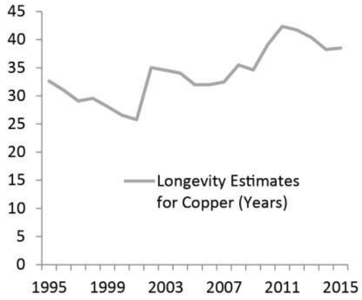






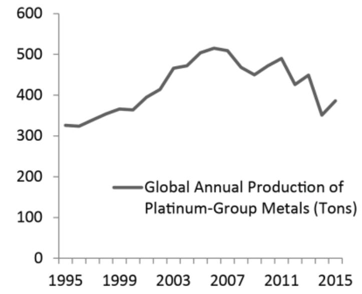


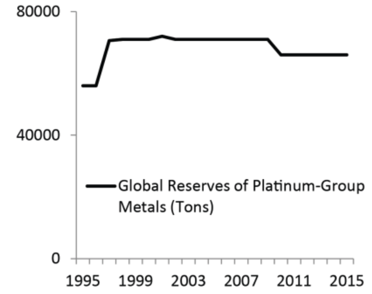


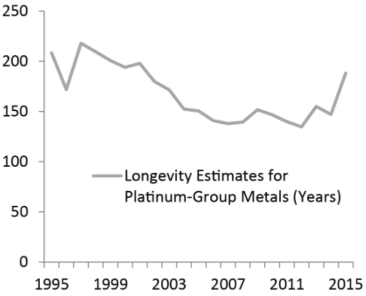


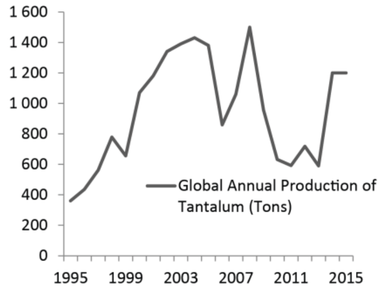
	Peak Year	Comments
Gold	2022-2025	Global gold reserves can supply the demand equivalent of 2014 for only 18.6 years (cf. U.S. Geological Survey 2016, p.73)
Silver	n.d.	With use of 5-7 g/capita & year, silver reserves can last for about 50 years (Johnson et al. 2005; Gordon et al. 2006). However, recent estimates by the U.S. Geological Survey show that at the 2015 production rate, global stocks of silver will be exhausted within 20.8 years (2016, p.153).
Copper	2100	Global copper reserves will finish in 38.5 years with the rate of extraction in 2014 (U.S. Geological Survey 2016, p.55).

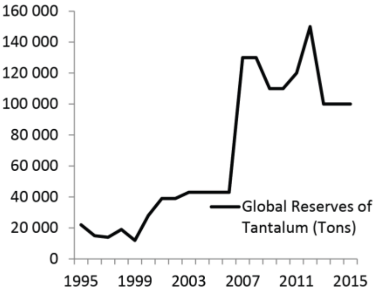
Appendices

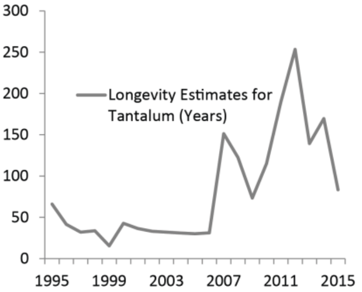


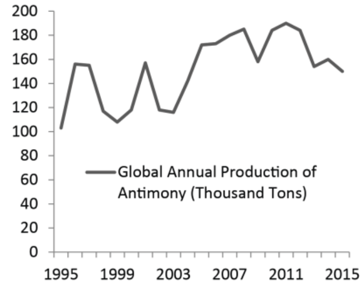


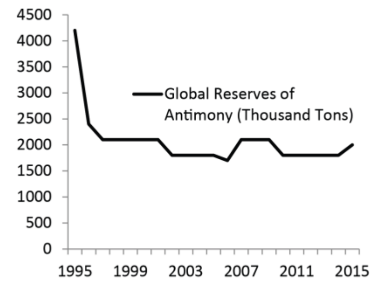


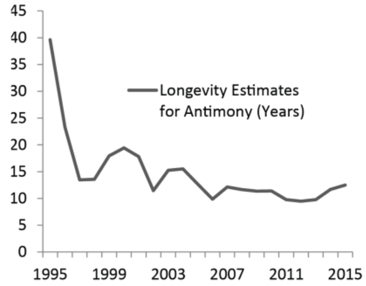


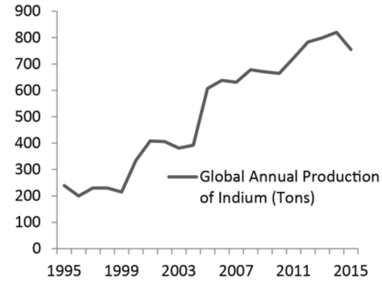


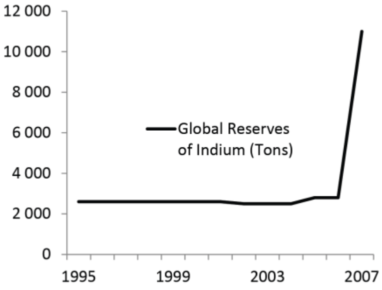


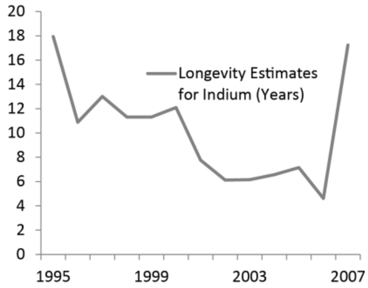












	Peak Year	Comments
Antimony	n.d	Only 13.3 years of reserves at the rate of extraction in 2014 (U.S. Geological Survey 2016, p.25) and a high supply risk (Graedel, Harper, Nassar, Nuss & Reck, 2015, p. 4259).
Indium	n.d.	Quantitative estimates of reserves not available (U.S. Geological Survey 2016), but a recent study (Graedel et al., 2015, p. 4259) confirms that indium supply is very high supply risk.
Platinum-group metals	n.d.	171 years of reserves of platinum-group metals (platinum and palladium) at the 2015 production rate, but the estimates were 188 years due a lower production rate due to a 5 month long strike in major mining companies in Africa (U.S. Geological Survey 2016, p.127). However, according to Gordon and Colleagues (2006, p.1213), platinum stocks will only last for 15 years.
Tantalum	n.d.	Global reserves will last for 83 years (U.S. Geological Survey 2016, p.167).

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9. Appended Papers 1-5

Paper 1:

Singh, J., Laurenti, R., Sinha, R. & Frostell, B. 2014. Progress and challenges to the global waste management system. *Waste Management & Research* 32 (9), 800–812. doi: 10.1177/0734242X14537868

Paper 2:

Laurenti, R. **Singh, J.**, Sinha, R., Potting, J. & Frostell, B. 2015. Unintended environmental consequences of improvement actions: A qualitative analysis of systems' structure and behavior. *Systems Research and Behavioral Science* (in press), p.n/a–n/a. doi: 10.1002/sres.2330

Paper 3:

Singh, J. & Ordoñez, I., 2015. Resource recovery from post-consumer waste: Important lessons for the upcoming circular economy. *Journal of Cleaner Production* (in press), p.n/a–n/a. doi: 10.1016/j.jclepro.2015.12.020

Paper 4:

Laurenti, R., Sinha, R., **Singh, J.** & Frostell, B. 2016. Towards addressing unintended environmental consequences: A planning framework. *Sustainable Development* 24(1), 1–17. doi:10.1002/sd.1601

Paper 5:

Singh, J. & Frostell, B. 2016. Towards a concerted approach to sustainable global physical resource management. *Manuscript*